



US012317535B2

(12) **United States Patent**
Yang et al.

(10) **Patent No.:** **US 12,317,535 B2**
(45) **Date of Patent:** **May 27, 2025**

(54) **INDEPENDENT CONTROL OF STACKED SEMICONDUCTOR DEVICE**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **18/423,738**

(22) Filed: **Jan. 26, 2024**

(65) **Prior Publication Data**

US 2024/0162347 A1 May 16, 2024

Related U.S. Application Data

(60) Continuation of application No. 17/815,396, filed on Jul. 27, 2022, now Pat. No. 11,916,145, which is a division of application No. 16/885,850, filed on May 28, 2020, now Pat. No. 11,502,199.

(51) **Int. Cl.**
H10D 30/62 (2025.01)
H10D 30/01 (2025.01)
H10D 84/01 (2025.01)
H10D 84/03 (2025.01)

(52) **U.S. Cl.**
CPC **H10D 30/62** (2025.01); **H10D 30/02A** (2025.01); **H10D 84/0158** (2025.01); **H10D 84/038** (2025.01); **H10D 30/6219** (2025.01)

(58) **Field of Classification Search**

CPC H01L 29/785; H01L 21/823431; H01L 29/66795; H01L 2029/7858

USPC 257/401
See application file for complete search history.

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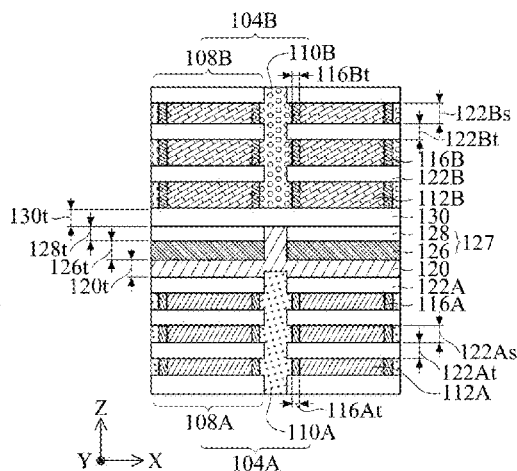
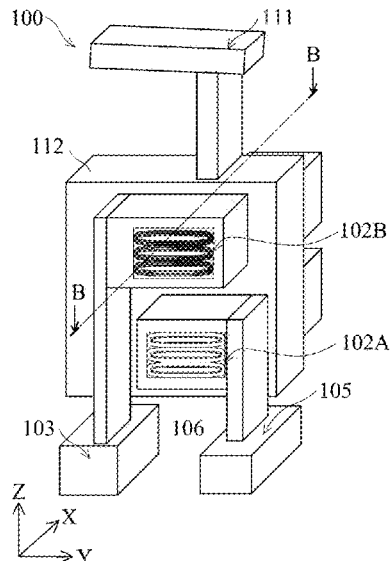
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(57) **ABSTRACT**

The present disclosure describes a semiconductor device includes a first fin structure, an isolation structure in contact with a top surface of the first fin structure, a substrate layer in contact with the isolation structure, an epitaxial layer in contact with the isolation structure and the substrate layer, and a second fin structure above the first fin structure and in contact with the epitaxial layer.

20 Claims, 13 Drawing Sheets



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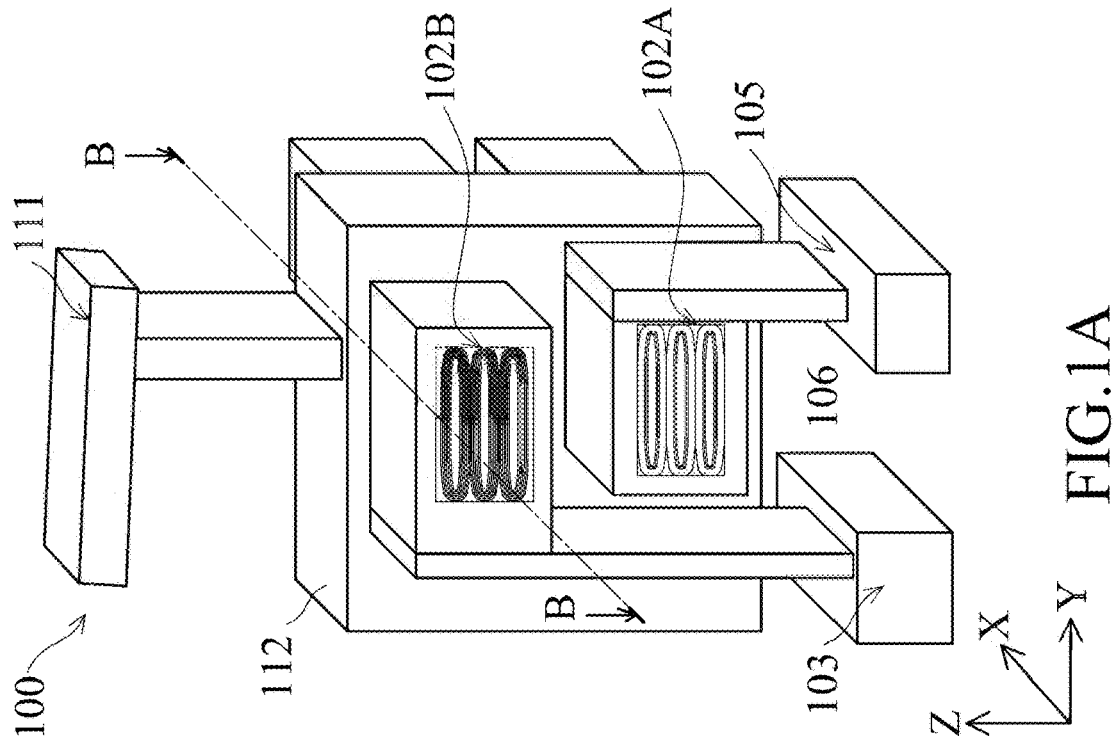


FIG. 1A

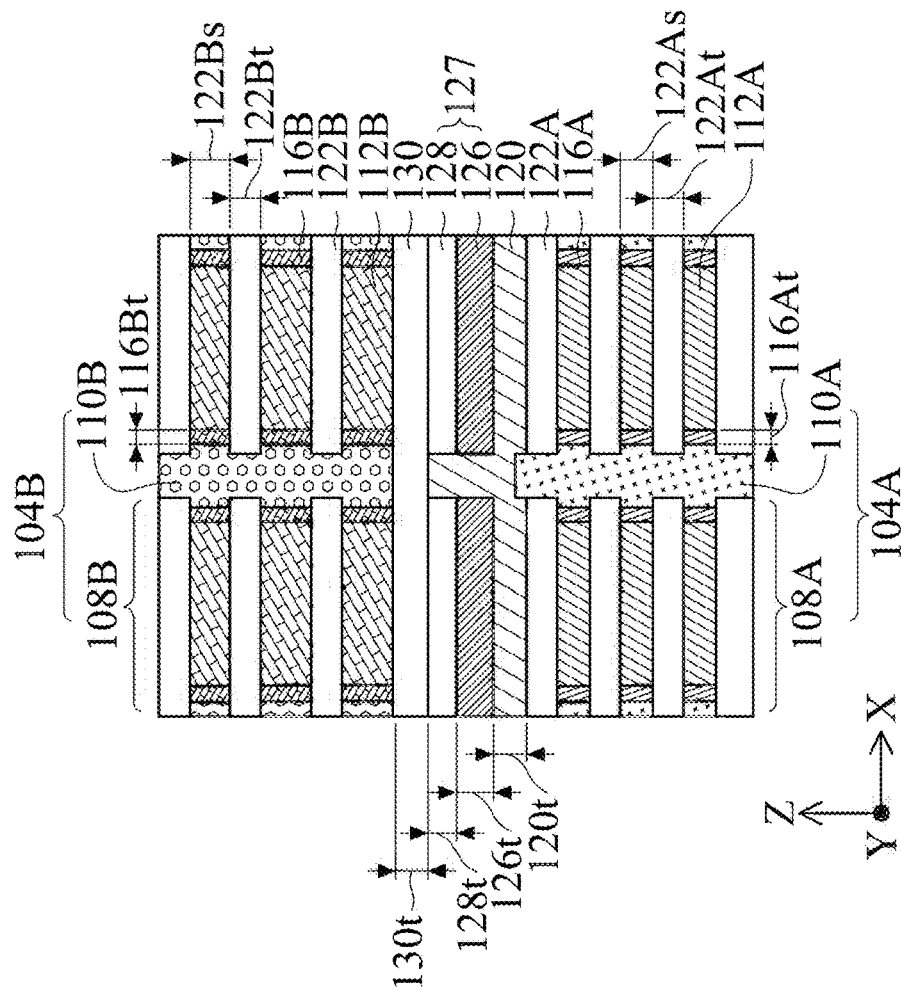


FIG. 1B

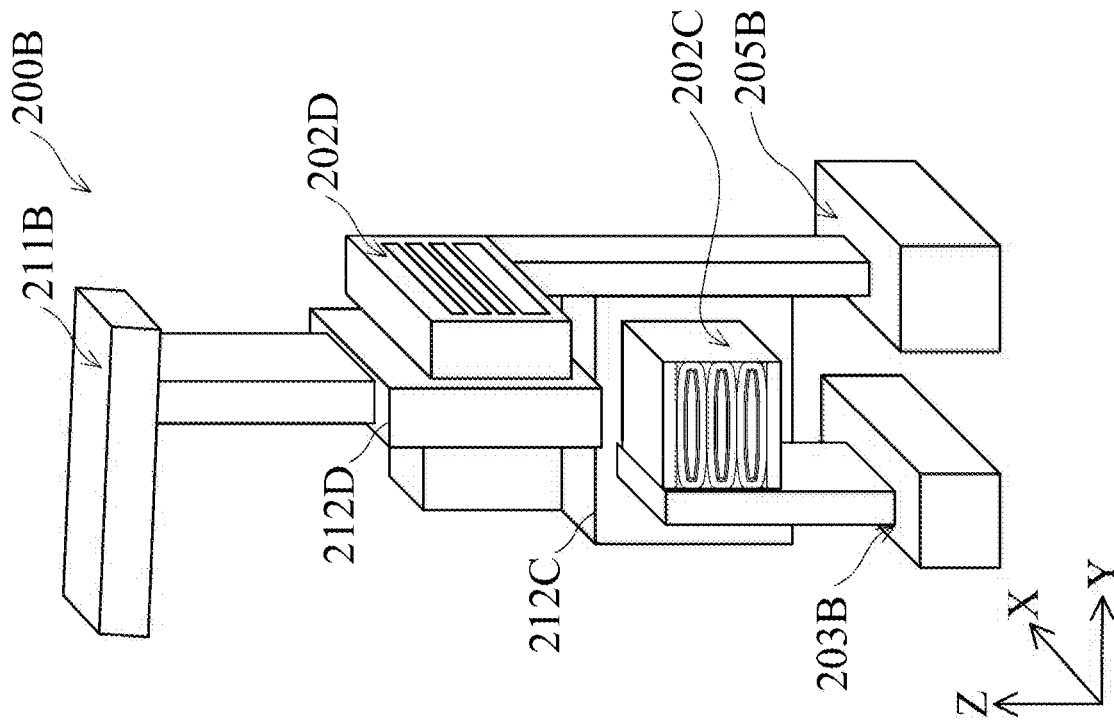


FIG. 2B

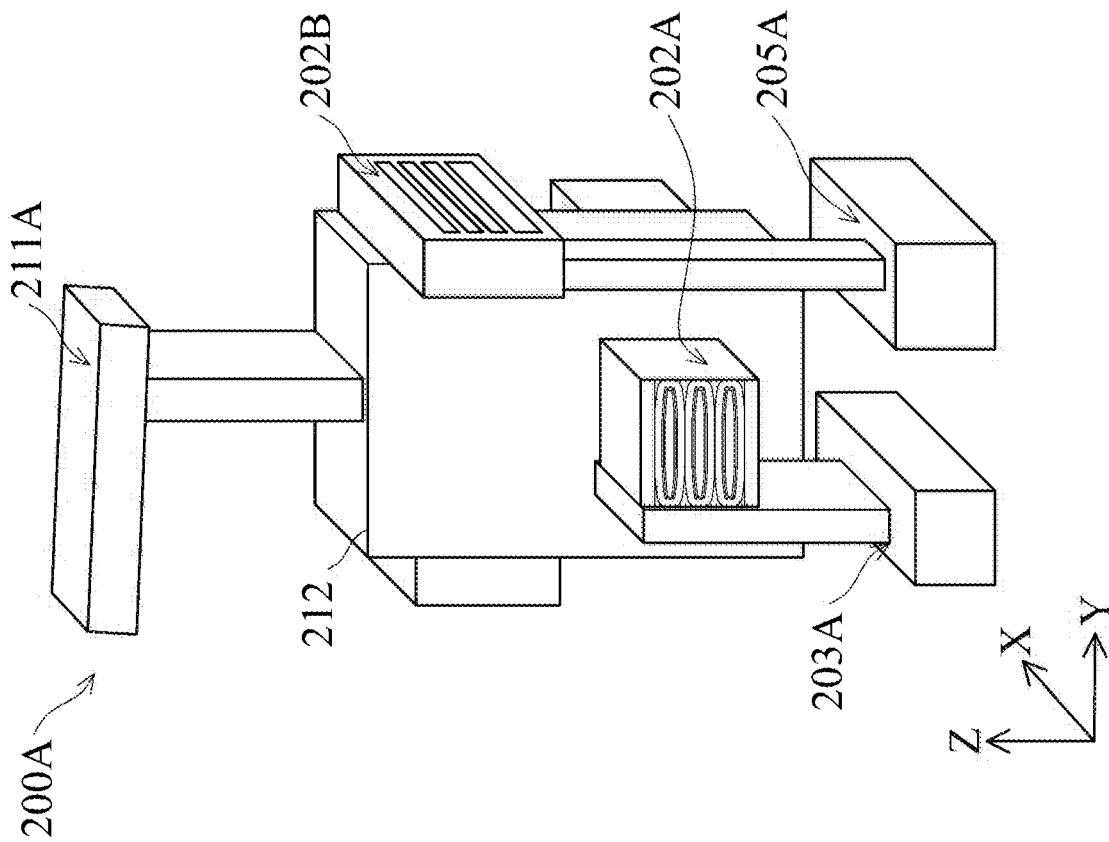


FIG. 2A

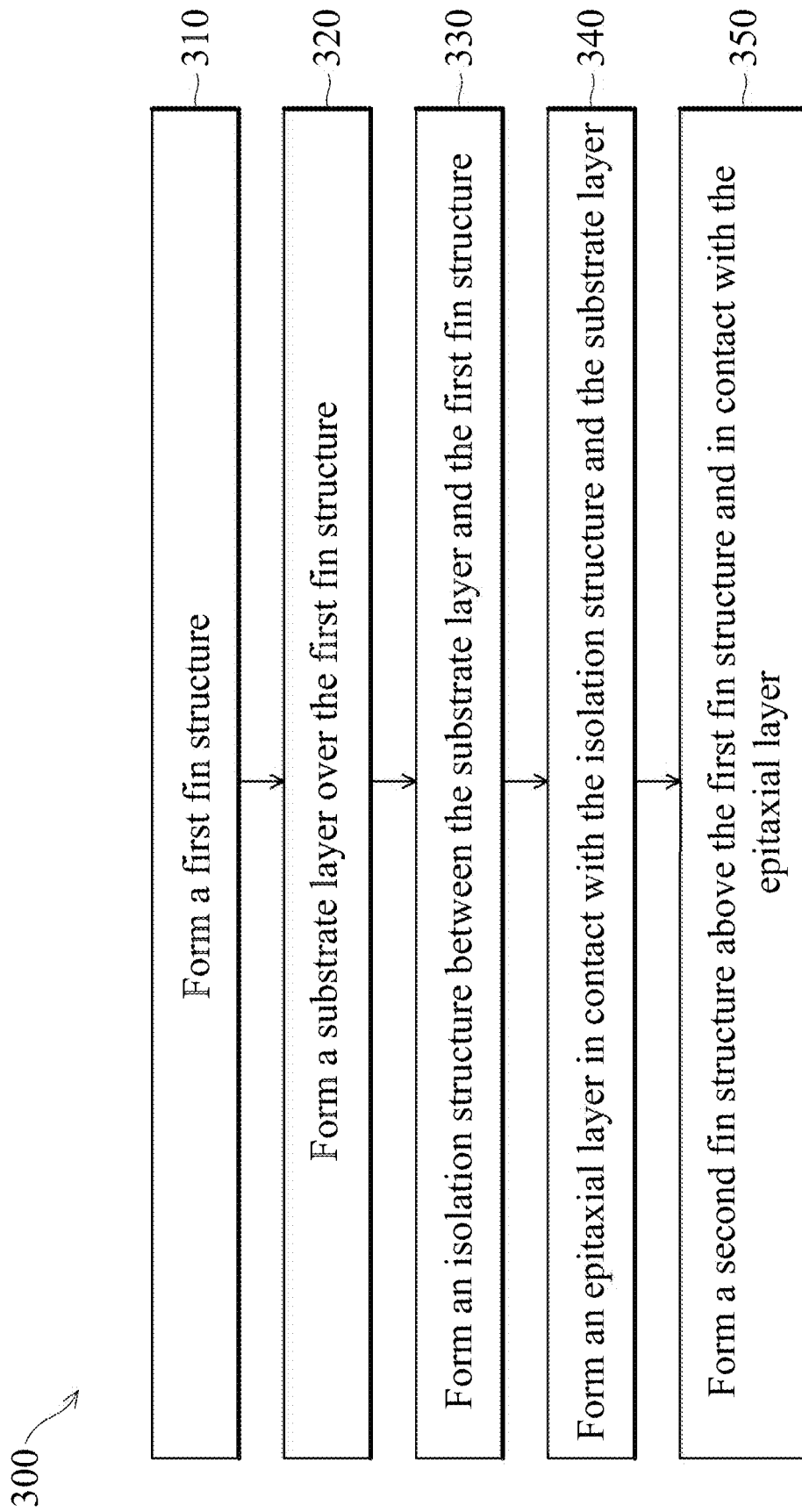


FIG.3

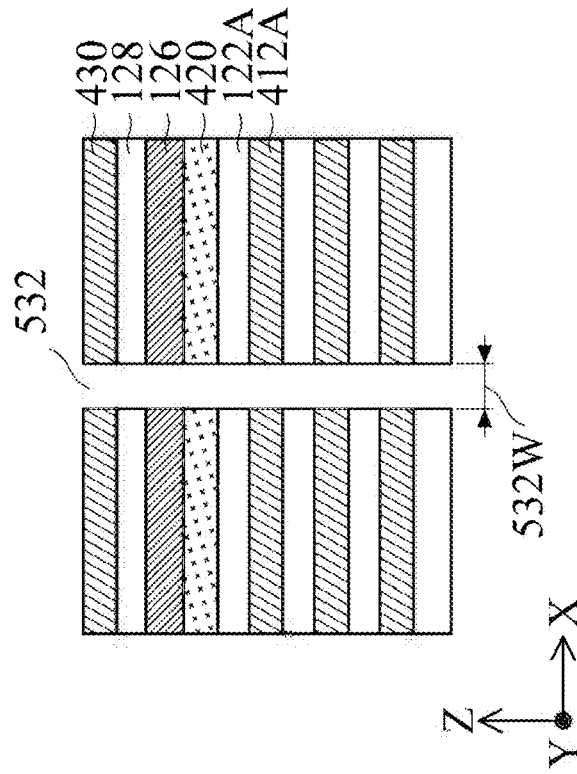


FIG. 4

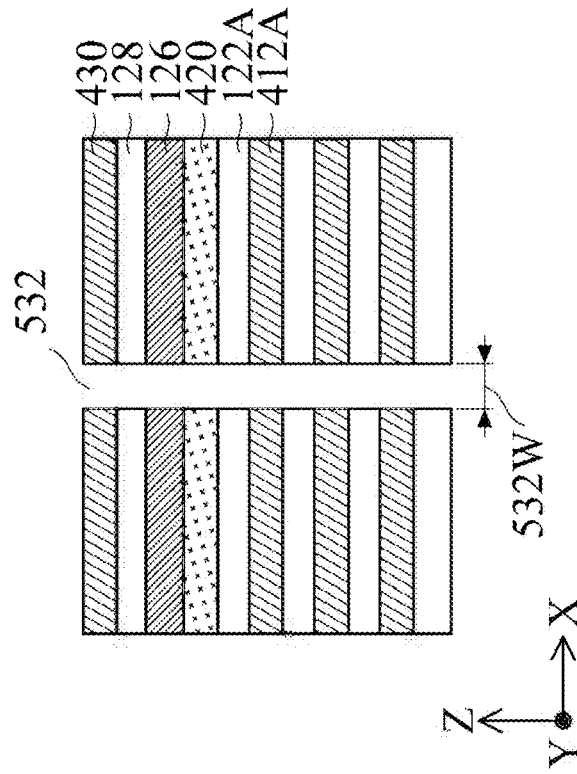


FIG. 5

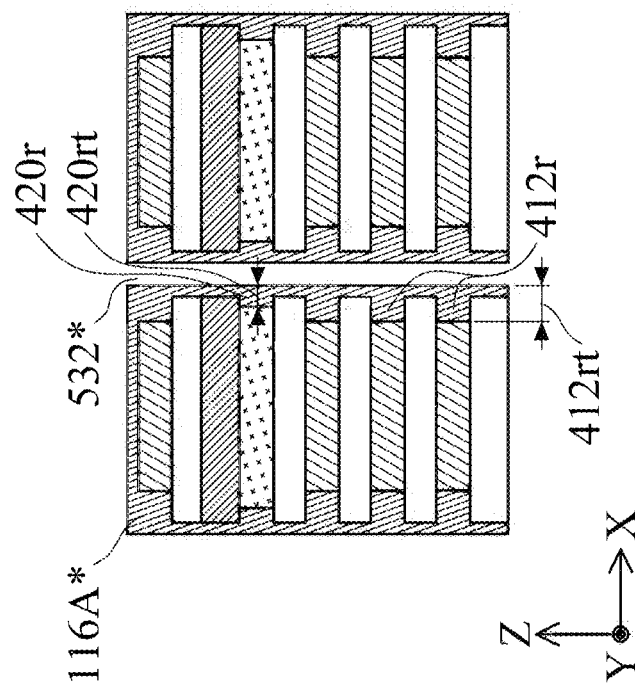


FIG. 6

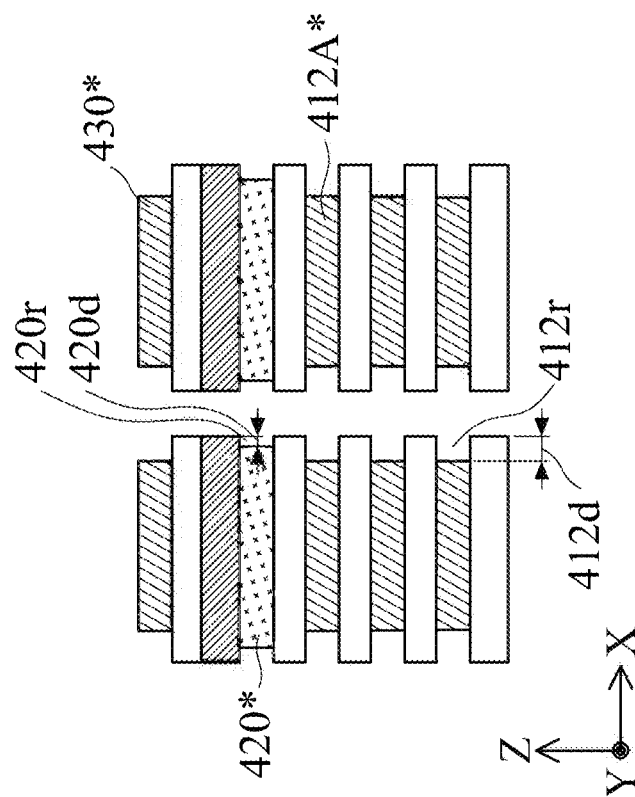


FIG. 7

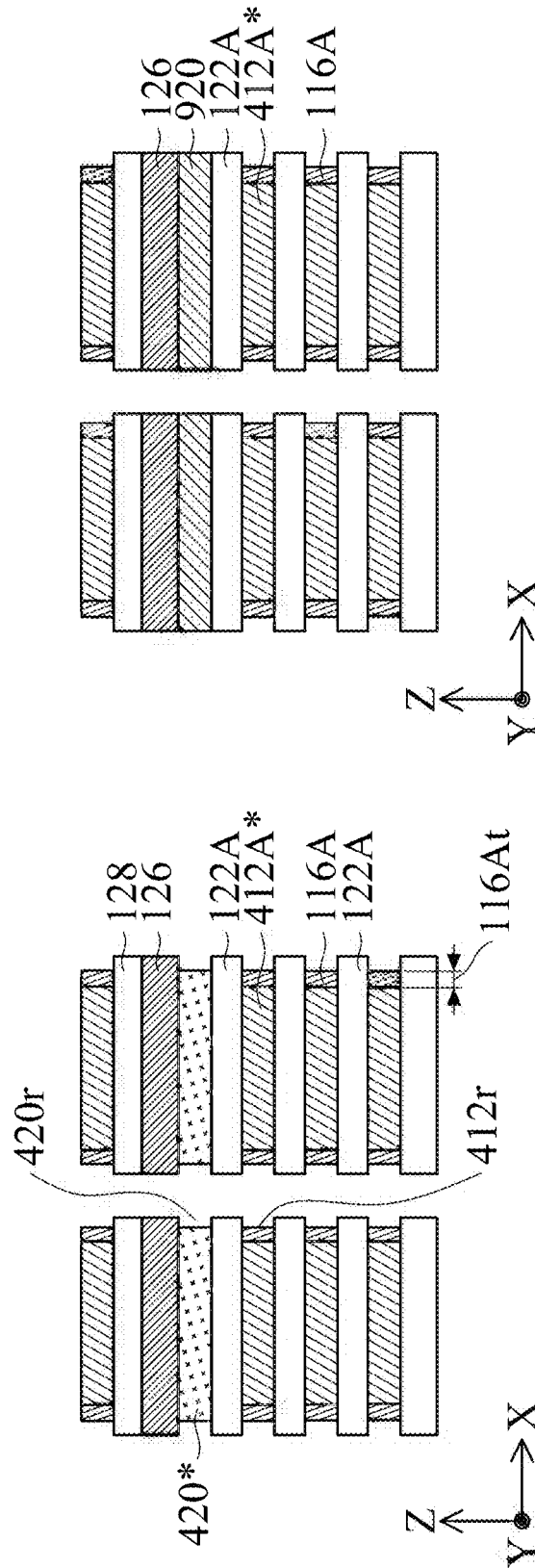


FIG. 8

FIG. 9

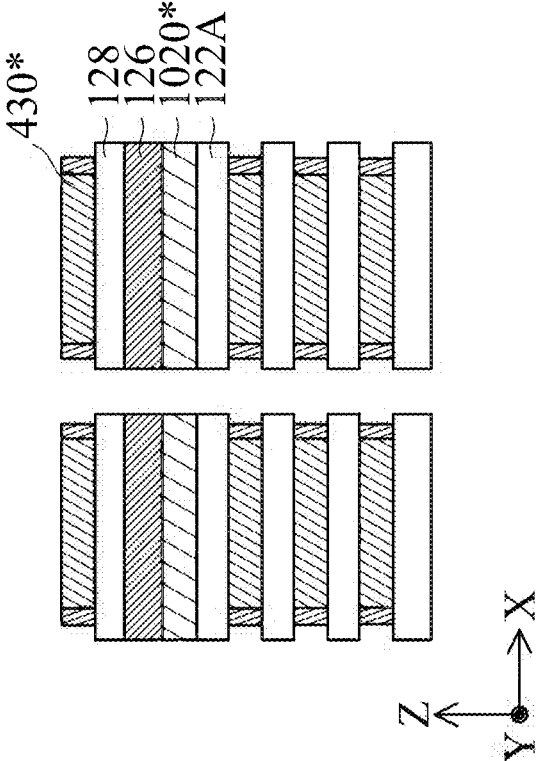


FIG.11

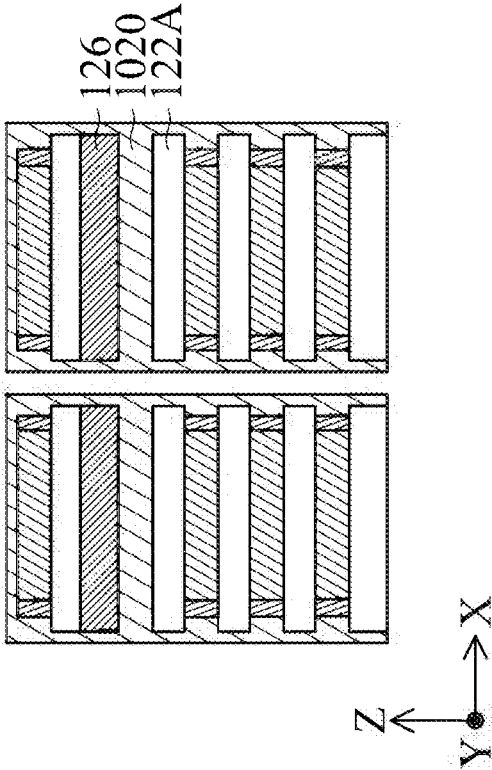


FIG.10

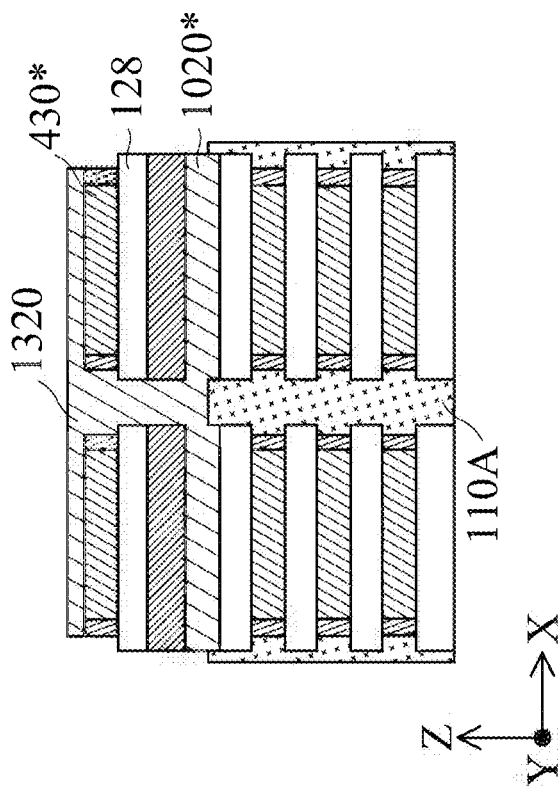


FIG.13

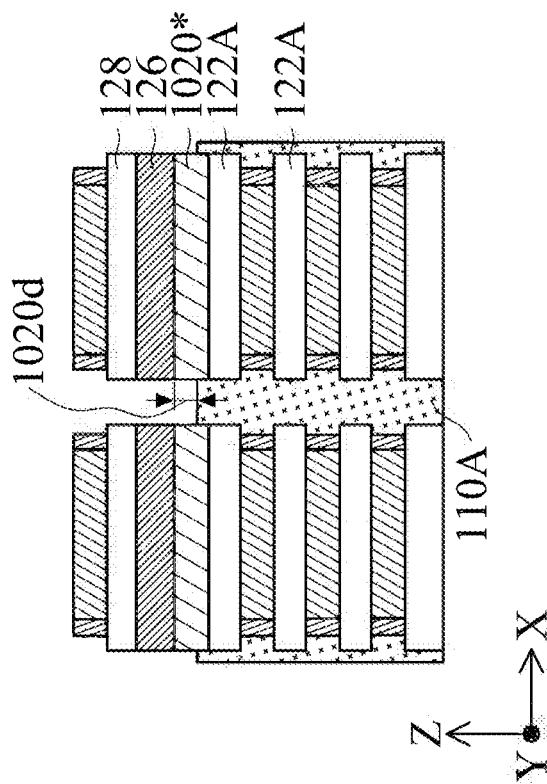


FIG.12

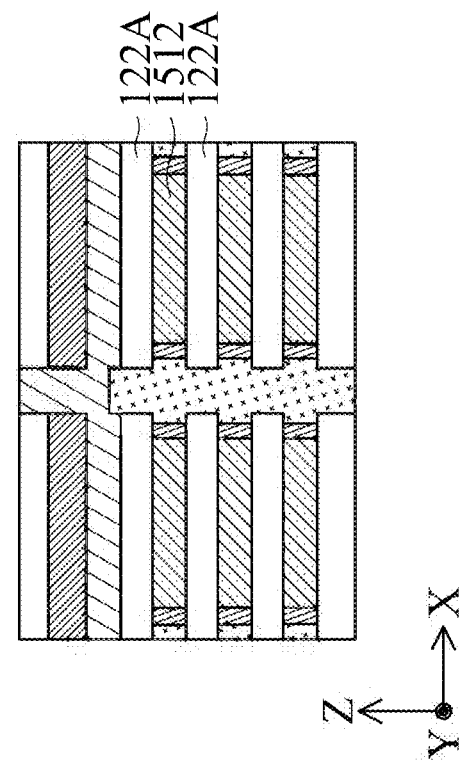


FIG.14

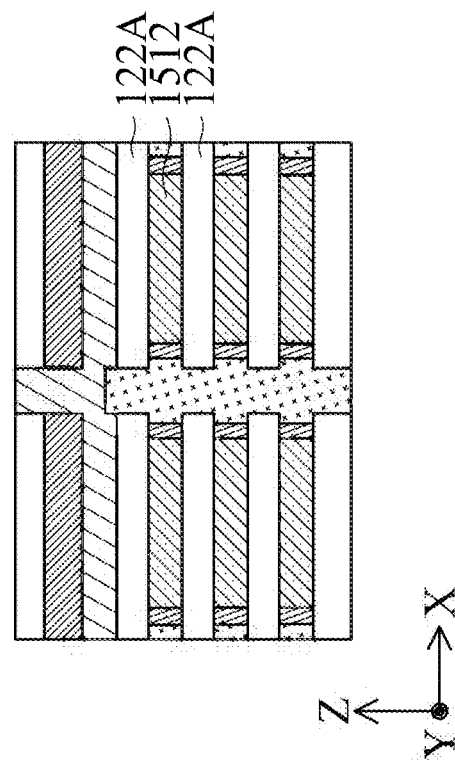


FIG.15

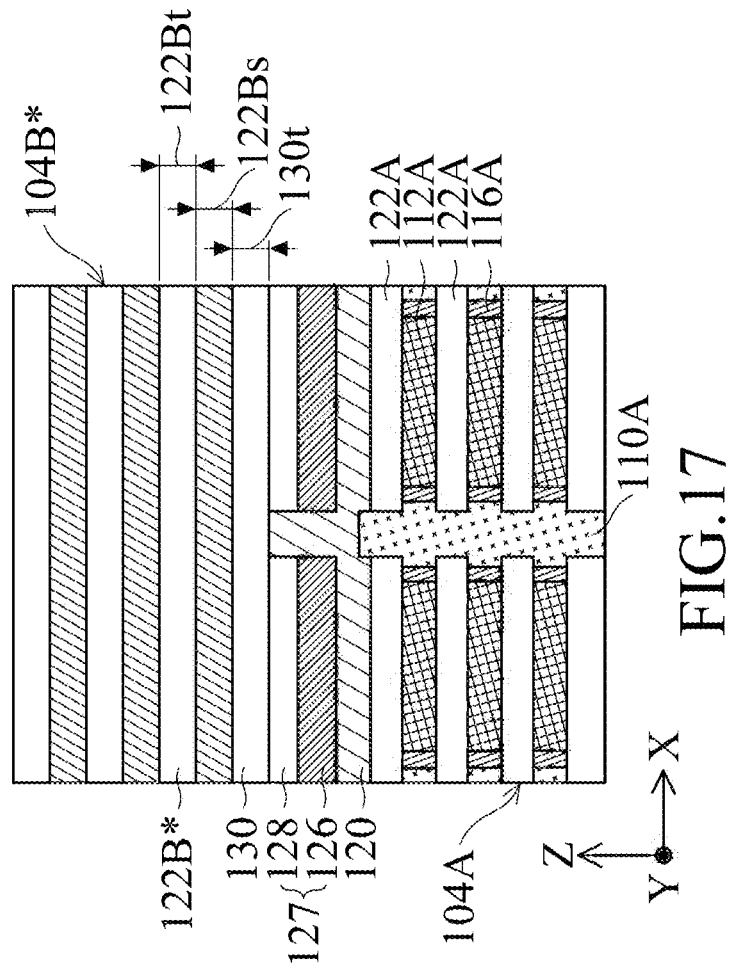


FIG. 17

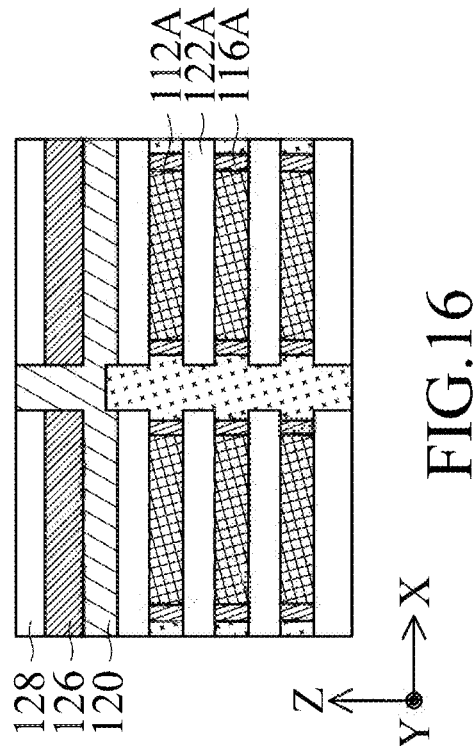


FIG. 16

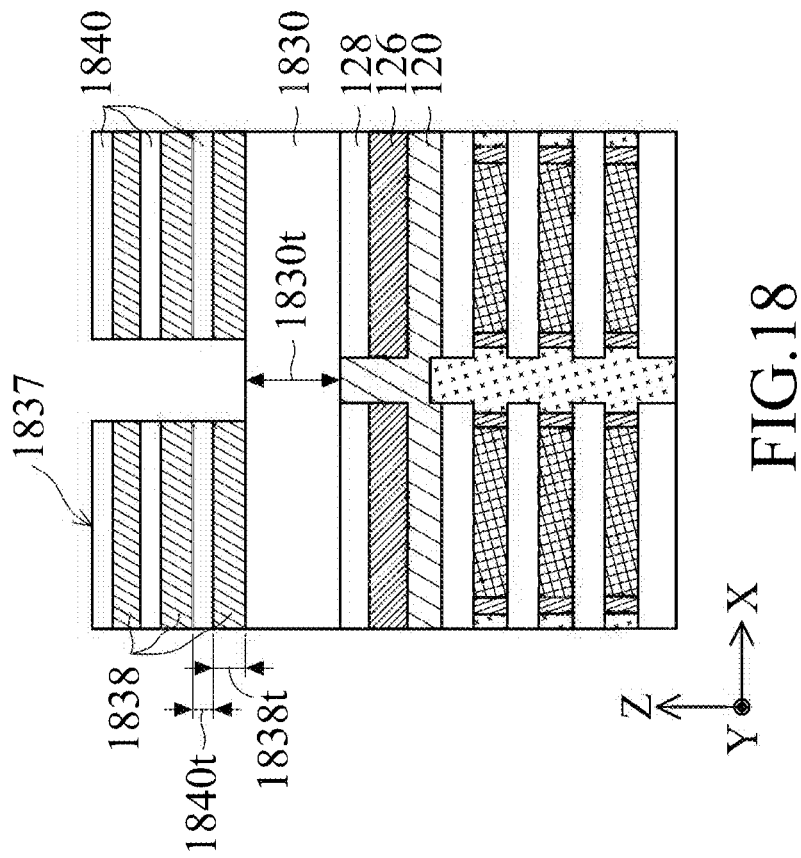


FIG. 18

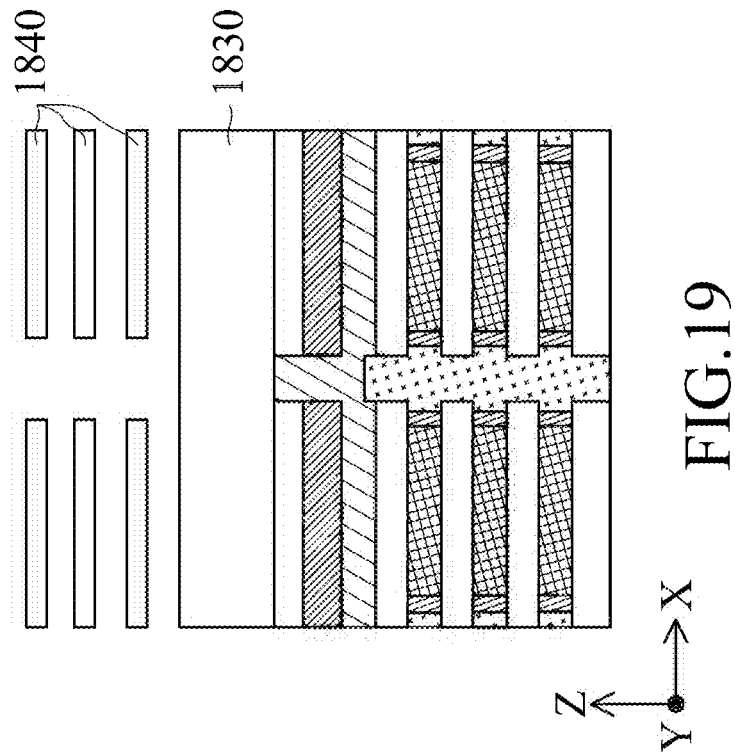
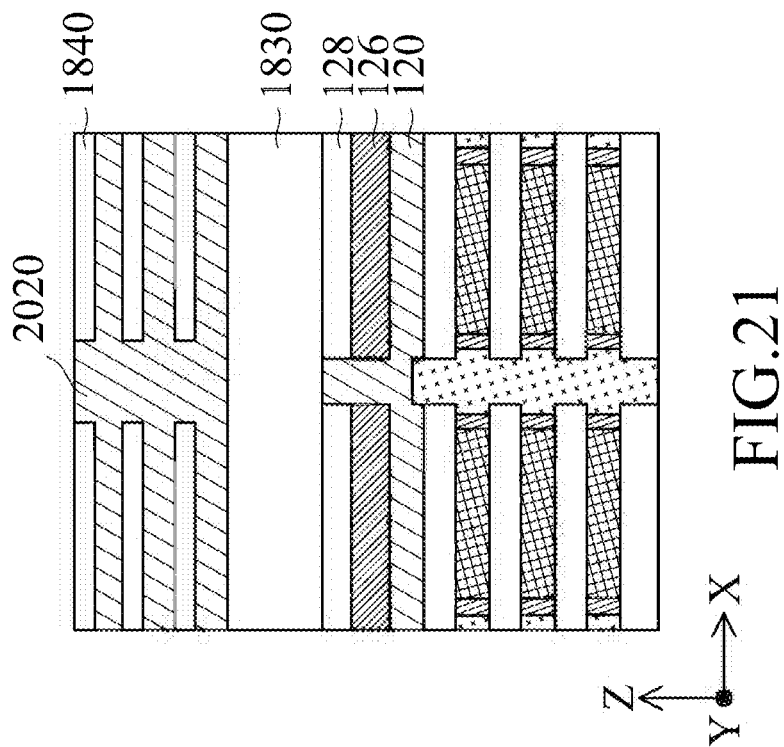
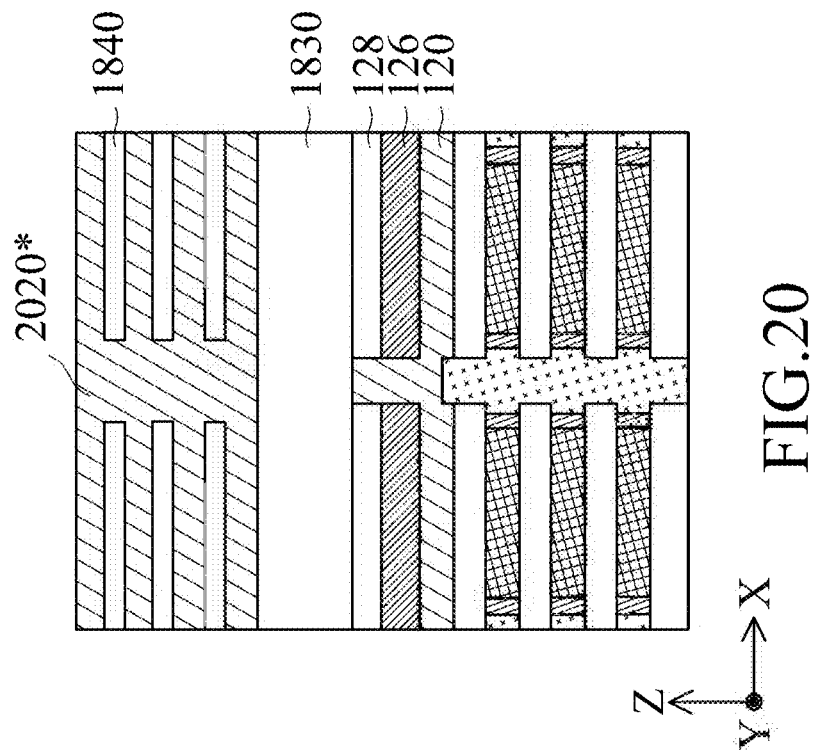


FIG. 19



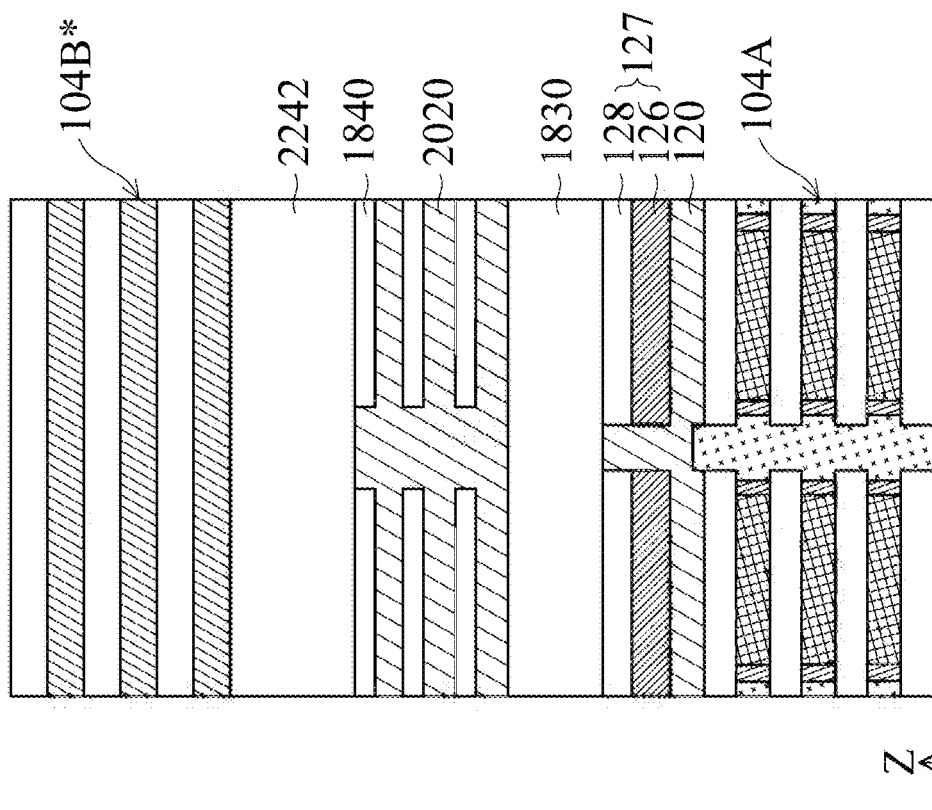


FIG. 23

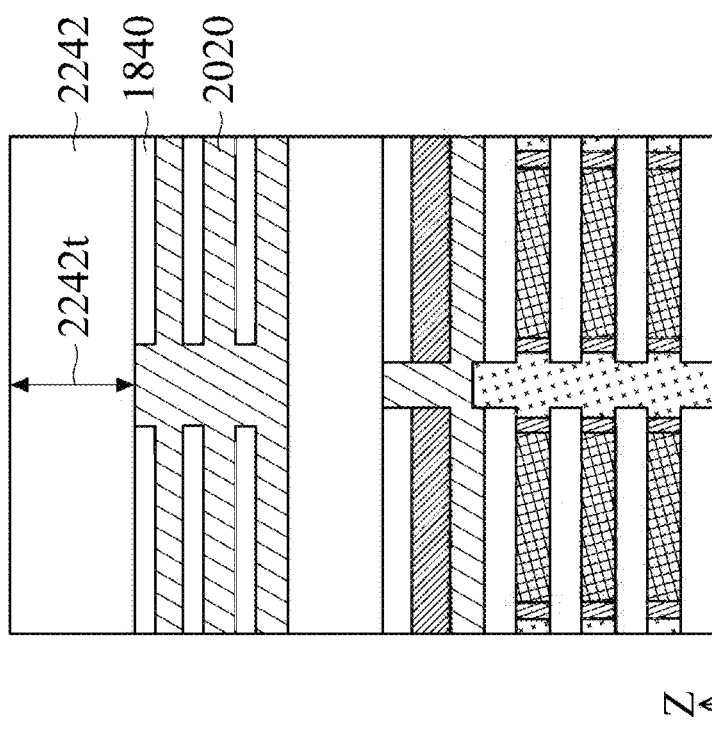


FIG. 22

INDEPENDENT CONTROL OF STACKED SEMICONDUCTOR DEVICE

CROSS-REFERENCE TO RELATED APPLICATION

This application is a continuation of U.S. Non-Provisional patent application Ser. No. 17/815,396, filed on Jul. 27, 2022, titled "Independent Control of Stacked Semiconductor Device," which is a divisional of U.S. Non-Provisional patent application Ser. No. 16/885,850, filed on May 28, 2020, now U.S. Pat. No. 11,502,199, titled "Independent Control of Stacked Semiconductor Device," which are incorporated by reference herein in their entireties.

BACKGROUND

With advances in semiconductor technology, there has been increasing demand for higher storage capacity, faster processing systems, higher performance, and lower costs. To meet these demands, the semiconductor industry continues to scale down the dimensions of semiconductor devices, such as metal oxide semiconductor field effect transistors (MOSFETs), including planar MOSFETs and fin field effect transistors (finFETs). Such scaling down has increased the complexity of semiconductor manufacturing processes.

BRIEF DESCRIPTION OF THE DRAWINGS

Aspects of the present disclosure are best understood from the following detailed description when read with the accompanying figures. It is noted that, in accordance with common practice in the industry, various features are not drawn to scale. In fact, the dimensions of the various features may be arbitrarily increased or reduced for clarity of discussion.

FIGS. 1A and 1B illustrate an isometric view and a partial cross-sectional view of a vertically stacked semiconductor device, respectively, in accordance with some embodiments.

FIGS. 2A and 2B illustrate isometric views of a crossover-stacked semiconductor device with a vertical gate and a crossover-stacked semiconductor device with a rotated gate, respectively, in accordance with some embodiments.

FIG. 3 is a flow diagram of a method for fabricating a stacked semiconductor device, in accordance with some embodiments.

FIGS. 4-17 illustrate partial cross-sectional views of a vertically stacked semiconductor device at various stages of its fabrication process, in accordance with some embodiments.

FIGS. 18-23 illustrate partial cross-sectional views of a vertically stacked semiconductor device with additional isolation structures at various stages of its fabrication process, in accordance with some embodiments.

Illustrative embodiments will now be described with reference to the accompanying drawings. In the drawings, like reference numerals generally indicate identical, functionally similar, and/or structurally similar elements.

DETAILED DESCRIPTION

The following disclosure provides many different embodiments, or examples, for implementing different features of the provided subject matter. Specific examples of components and arrangements are described below to simplify the present disclosure. These are, of course, merely examples and are not intended to be limiting. For example,

the formation of a first feature over a second feature in the description that follows may include embodiments in which the first and second features are formed in direct contact, and may also include embodiments in which additional features may be formed between the first and second features, such that the first and second features may not be in direct contact. As used herein, the formation of a first feature on a second feature means the first feature is formed in direct contact with the second feature. In addition, the present disclosure may repeat reference numerals and/or letters in the various examples. This repetition does not in itself dictate a relationship between the various embodiments and/or configurations discussed.

Further, spatially relative terms, such as "beneath," "below," "lower," "above," "upper," and the like, may be used herein for ease of description to describe one element or feature's relationship to another element(s) or feature(s) as illustrated in the figures. The spatially relative terms are intended to encompass different orientations of the device in use or operation in addition to the orientation depicted in the figures. The apparatus may be otherwise oriented (rotated 90 degrees or at other orientations) and the spatially relative descriptors used herein may likewise be interpreted accordingly.

It is noted that references in the specification to "one embodiment," "an embodiment," "an example embodiment," "exemplary," etc., indicate that the embodiment described may include a particular feature, structure, or characteristic, but every embodiment may not necessarily include the particular feature, structure, or characteristic. Moreover, such phrases do not necessarily refer to the same embodiment. Further, when a particular feature, structure or characteristic is described in connection with an embodiment, it would be within the knowledge of one skilled in the art to effect such feature, structure or characteristic in connection with other embodiments whether or not explicitly described.

It is to be understood that the phraseology or terminology herein is for the purpose of description and not of limitation, such that the terminology or phraseology of the present specification is to be interpreted by those skilled in relevant art(s) in light of the teachings herein.

The term "nominal" as used herein refers to a desired, or target, value of a characteristic or parameter for a component or a process operation, set during the design phase of a product or a process, together with a range of values above and/or below the desired value. The range of values is typically due to slight variations in manufacturing processes or tolerances.

As used herein, the term "etch selectivity" refers to the ratio of the etch rates of two different materials under the same etching conditions.

As used herein, the term "substrate" describes a material onto which subsequent material layers are added. The substrate itself may be patterned. Materials added on top of the substrate may be patterned or may remain unpatterned. Furthermore, the substrate may be a wide array of semiconductor materials, such as silicon, germanium, gallium arsenide, indium phosphide, etc. Alternatively, the substrate may be made from an electrically non-conductive material, such as glass and sapphire wafer.

As used herein, the term "high-k" refers to a high dielectric constant. In the field of semiconductor device structures and manufacturing processes, high-k refers to a dielectric constant that is greater than the dielectric constant of SiO₂ (e.g., greater than about 3.9).

As used herein, the term “low-k” refers to a small dielectric constant. In the field of semiconductor device structures and manufacturing processes, low-k refers to a dielectric constant that is less than the dielectric constant of SiO₂ (e.g., less than about 3.9).

As used herein, the term “p-type” defines a structure, layer, and/or region as being doped with p-type dopants, such as boron.

As used herein, the term “n-type” defines a structure, layer, and/or region as being doped with n-type dopants, such as phosphorus.

As used herein, the term “vertical,” means nominally along a direction perpendicular to the surface of a substrate.

As used herein, the term “crossover,” means structures along directions crossing at a point.

The terms “about” and “substantially” as used herein indicate the value of a given quantity that can vary based on a particular technology node associated with the subject semiconductor device. In some embodiments, based on the particular technology node, the terms “about” and “substantially” can indicate a value of a given quantity that varies within, for example, 5% of a target value (e.g., $\pm 1\%$, $\pm 2\%$, $\pm 3\%$, $\pm 4\%$, $\pm 5\%$ of the target value).

Embodiments of the fin structures disclosed herein may be patterned by any suitable method. For example, the fin structures may be patterned using one or more photolithography processes, including double-patterning or multi-patterning processes. Double-patterning or multi-patterning processes can combine photolithography and self-aligned processes, forming patterns that have, for example, pitches smaller than what is otherwise obtainable using a single, direct photolithography process. For example, a sacrificial layer is formed over a substrate and patterned using a photolithography process. Spacers are formed alongside the patterned sacrificial layer using a self-aligned process. The sacrificial layer is then removed, and the remaining spacers may then be used to pattern the fin structures.

With advances in semiconductor technology, multi-gate devices have been introduced in an effort to improve gate control by increasing gate-channel coupling, reduce off-state current, and reduce short-channel effects (SCEs). One such multi-gate device that has been introduced is the gate-all-around fin field effect transistor (GAA finFET). The GAA finFET provides a channel in a stacked nanosheet/nanowire configuration. The GAA finFET derives its name from the gate structure that can extend around the channel and provide gate control of the channel on two or four sides of the channel. GAA finFETs are compatible with MOSFET manufacturing processes and their structure allows them to be scaled while maintaining gate control and mitigating SCEs.

GAA finFETs can be planar GAA finFETs with n-type and p-type GAA finFETs in a same plane and fabricated from the same stack of nanosheets/nanowires. With increasing demand for lower power consumption, high performance, and small area (collectively referred to as “PPA”) of semiconductor devices, planar GAA finFETs can have their challenges. For example, n-type and p-type planar GAA finFETs have the same nanosheet/nanowire dimensions and spacings between the stacked nanosheets/nanowires, thus having the same space for n-type and p-type work function metal fill. N-type and p-type GAA finFETs may need different spaces to provide flexibility in the n-type and p-type work function metal fill. In addition, n-type and p-type planar GAA finFETs have inner spacer materials with the same dielectric constant (also referred to as “k value”). N-type and p-type GAA finFETs may need different inner

spacer materials for different device performance requirements. In addition, the nanosheet/nanowire mixed threshold voltage boundary can shift during an etch process of planar GAA finFETs. The nanosheet/nanowire mixed threshold voltage boundary shift may degrade device performance of planar GAA finFETs. Further, planar GAA finFETs have the same nanosheet/nanowire dimensions and spacings between the stacked nanosheets/nanowires, but multiple threshold voltages require different thicknesses of work function metal. Therefore, incorporating multiple threshold voltages in planar GAA finFETs through work function metal nanosheet/nanowire patterning can be challenging.

Various embodiments in accordance with the present disclosure provide methods for forming a stacked semiconductor device. According to some embodiments, the stacked semiconductor device can include a top fin structure along a direction vertically stacked on top of a bottom fin structure along the same direction (referred to as “vertically stacked”). In some embodiments, the vertically stacked top and bottom fin structures can each independently control their nanosheet/nanowire dimensions and spacings. In some embodiments, the top fin structure oriented along a first direction can be stacked on top of a bottom fin structure oriented along a second direction, where the first and second directions are oriented about 90 degrees relative to one another. This is also referred to herein “crossover-stacked.” In some embodiments, a crossover-stacked semiconductor device can provide compact metal interconnect place and route for the top and bottom fin structures, therefore improving PPA performance. In some embodiments, a crossover-stacked semiconductor device can include a top gate structure rotated by some degrees relative to the bottom gate structure, such as about 90 degrees (referred to as “rotated gate”). In some embodiments, a crossover-stacked semiconductor device with a rotated gate can provide further compact metal interconnect route and place to reduce parasitic resistance and capacitance, thus improving PPA performance. In some embodiments, an isolation layer can isolate the top fin structure and the bottom fin structure. In some embodiments, additional isolation layers between the top fin structure and the bottom fin structure can improve the isolation.

FIG. 1A illustrates an isometric view of a vertically stacked semiconductor device **100** having a GAA finFET **102B** vertically stacked on top of a GAA finFET **102A**, according to some embodiments. FIG. 1B illustrates a partial cross-sectional view along line B-B of vertically stacked semiconductor device **100**, according to some embodiments. In some embodiments, FIGS. 1A and 1B show a portion of an IC layout where the spacing between the fin structures (e.g., the fin pitch), the dimensions of the fin structures, and the dimensions of the gate structures can be similar or different from the ones shown in FIGS. 1A and 1B. Additionally, the isometric and cross-sectional views of semiconductor device **100** in FIGS. 1A and 1B and the subsequent figures are for illustrative purposes. FIGS. 1A and 1B and the subsequent figures may not reflect the actual geometry of the actual structures, features, or films.

Referring to FIGS. 1A and 1B, vertically stacked semiconductor device **100** can include GAA finFETs **102A** and **102B**, source/drain interconnects **103** and **105** connected to GAA finFETs **102A** and **102B**, a gate structure **112**, and a gate interconnect **113** connected to gate structure **112**. GAA finFETs **102A** and **102B** can further include fin structures **104A** and **104B**, gate structures **112A** and **112B**, inner spacer structures **116A** and **116B**, an isolation structure **120**, a doping layer **126**, and a semiconductor layer **128**.

In some embodiments, GAA finFETs **102A** and **102B** can be both p-type finFETs (PFETs), both n-type finFETs (NFETs), or one of each conductivity type finFET. In some embodiments, GAA finFETs **102A** can be p-type (also referred to as “PFET **102A**”) and GAA finFETs **102B** can be n-type (also referred to as “NFET **102B**”). Though FIGS. **1A** and **1B** show two GAA finFETs, vertically stacked semiconductor device **100** can have any number of GAA finFETs. Also, though FIGS. **1A** and **1B** show one gate structure **112**, vertically stacked semiconductor device **100** can have additional gate structures similar and parallel to gate structure **112**. In addition, semiconductor device **100** can be incorporated into an integrated circuit through the use of other structural components, such as contacts, conductive vias, conductive lines, dielectric layers, passivation layers, etc., that are not shown for simplicity. The discussion of elements of GAA finFETs **104A** and **104B** with the same annotations applies to each other, unless mentioned otherwise.

As shown in FIG. **1A**, GAA finFET **102A** can be formed on a substrate **106**. Substrate **106** can be a semiconductor material, such as silicon (Si). In some embodiments, substrate **106** can include a crystalline silicon substrate (e.g., wafer). In some embodiments, substrate **106** can include (i) an elementary semiconductor, such as germanium (Ge); (ii) a compound semiconductor including silicon carbide (SiC), silicon arsenide (SiAs), gallium arsenide (GaAs), gallium phosphide (GaP), indium phosphide (InP), indium arsenide (InAs), indium antimonide (InSb), and/or a III-V semiconductor material; (iii) an alloy semiconductor including silicon germanium (SiGe), silicon germanium carbide (SiGeC), germanium stannum (GeSn), silicon germanium stannum (SiGeSn), gallium arsenic phosphide (GaAsP), gallium indium phosphide (GaInP), gallium indium arsenide (GaInAs), gallium indium arsenic phosphide (GaInAsP), aluminum indium arsenide (AlInAs), and/or aluminum gallium arsenide (AlGaAs); (iv) a silicon-on-insulator (an) structure; (v) a silicon germanium (SiGe)-on insulator structure (SiGeOI); (vi) germanium-on-insulator (GeOI) structure; or (vii) a combination thereof. Further, substrate **106** can be doped depending on design requirements (e.g., p-type substrate or n-type substrate). In some embodiments, substrate **106** can be doped with p-type dopants (e.g., boron, indium, aluminum, or gallium) or n-type dopants (e.g., phosphorus or arsenic).

As shown in FIGS. **1A** and **1B**, GAA finFET **102B** can be formed on epitaxial layer **130**, semiconductor layer **128**, and doping layer **126**. In some embodiments, semiconductor layer **128** and doping layer **126** can serve as a substrate layer **127** for GAA finFET **102B**. Doping layer **126** can be disposed on GAA finFET **102A** and include semiconductor materials similar to or different from substrate **106**. In some embodiments, doping layer **126** can include Si. In some embodiments, the semiconductor materials of doping layer **126** can be in-situ doped during its epitaxial growth process using: (i) p-type dopants, such as boron, indium, and gallium; and/or (ii) n-type dopants, such as phosphorus and arsenic. For p-type in-situ doping, p-type doping precursors, such as diborane (B₂H₆), boron trifluoride (BF₃), and other p-type doping precursors, can be used. For n-type in-situ doping, n-type doping precursors, such as phosphine (PH₃), arsine (AsH₃), and other n-type doping precursors, can be used. Doping layer **126** can have a vertical dimension **126t** (e.g., thicknesses) along a Z-axis ranging from about 5 nm to about 10 nm. In some embodiments, doping layer **126** can be doped with a different conductivity type from substrate **106**, such as n-type for substrate **106** and p-type for doping

layer **126**. In some embodiments, doping layer **126** can serve as an implant well for GAA finFETs **102B**. Other dimensions, materials, and doping type for doping layer **126** are within the scope and spirit of this disclosure.

Semiconductor layer **128** can be disposed on doping layer **126** and include semiconductor materials similar to or different from doping layer **126**. In some embodiments, semiconductor layer **128** can include Si. The semiconductor materials of semiconductor layers **122** can be undoped or can be in-situ doped using a similar epitaxial growth process as doping layer **126**. Semiconductor layer **128** can have a thickness **128t** along a Z-axis ranging from about 12 nm to about 20 nm. In some embodiments, semiconductor layer **128** can help subsequent growth of epitaxial layer **130** and fin structure **104B**.

Epitaxial layer **130** can be disposed on semiconductor layer **128** and isolation structure **120**. In some embodiments, epitaxial layer **130** can be epitaxially grown similar to semiconductor layer **128**. In some embodiments, epitaxial layer **130** can include Si without any substantial amount of Ge. In some embodiments, epitaxial layer **130** can be epitaxially grown on semiconductor layer **128** and merge over the portion of isolation structure **120** on epitaxial fin regions **110A**. In some embodiments, epitaxial layer **130** can have a thickness **130t** along a Z-axis ranging from about 10 nm to about 20 nm.

Semiconductor device **100** can further include fin structures **104A** and **104B** extending along an X-axis and through GAA finFETs **102A** and **102B**, respectively. In some embodiments, fin structures **104A** and **104B** can each include stacked fin portions **108A** and **108B** and epitaxial fin regions **110A** and **110B**. Each of stacked fin portions **108A** and **108B** can include a stack of semiconductor layers **122A** and **122B**, which can be in the form of nanosheets or nanowires. Each of semiconductor layers **122A** and **122B** can form a channel region underlying gate structures **112A** and **112B** of GAA finFETs **102A** and **102B**, respectively.

In some embodiments, semiconductor layers **122A** and **122B** can include semiconductor materials similar to or different from substrate **106**. In some embodiments, each of semiconductor layers **122A** and **122B** can include silicon germanium (SiGe) with Ge in a range from about 5 atomic percent to about 50 atomic percent with any remaining atomic percent being Si or can include Si without any substantial amount of Ge. The semiconductor materials of semiconductor layers **122A** and **122B** can be undoped or can be in-situ doped using a similar epitaxial growth process as doping layer **126**. Semiconductor layers **122A** and **122B** can have respective thicknesses **122At** and **122Bt** along a Z-axis, each ranging from about 5 nm to about 12 nm. Semiconductor layers **122A** and **122B** can also have respective spacings **122As** and **122Bs** along a Z-axis between each other, each ranging from about 6 nm to about 16 nm. Other dimensions and materials for semiconductor layers **122A** and **122B** are within the scope and spirit of this disclosure. Though three layers of semiconductor layers **122A** and **122B** for each of GAA finFETs **102A** and **102B** are shown in FIGS. **1A** and **1B**, GAA finFETs **102A** and **102B** can each have any number of semiconductor layers **122A** and **122B**.

Referring to FIGS. **1A** and **1B**, epitaxial fin regions **110A** and **110B** can be disposed adjacent to stack fin portions **108A** and **108B**, respectively. In some embodiments, epitaxial fin regions **110A** and **110B** can have any geometric shape, such as a polygon, an ellipsis, and a circle. Epitaxial fin regions **110A** and **110B** can include an epitaxially-grown semiconductor material. In some embodiments, the epitaxially grown semiconductor material is the same material as

substrate **106**. In some embodiments, the epitaxially-grown semiconductor material includes a different material from substrate **106**. In some embodiments, the epitaxially-grown semiconductor material for epitaxial fin regions **110A** and **110B** can be the same as or different from each other. The epitaxially-grown semiconductor material can include: (i) a semiconductor material, such as germanium and silicon; (ii) a compound semiconductor material, such as gallium arsenide and aluminum gallium arsenide; or (iii) a semiconductor alloy, such as silicon germanium and gallium arsenide phosphide.

In some embodiments, epitaxial fin regions **110A** can be p-type for PFET **102A** (also referred to as “p-type epitaxial fin regions **110A**”) and epitaxial fin regions **110B** can be n-type for NFET **102B** (also referred to as “n-type epitaxial fin regions **110B**”). In some embodiments, p-type epitaxial fin regions **110A** can include SiGe and can be in-situ doped during an epitaxial growth process using p-type dopants, such as boron, indium, and gallium. In some embodiments, p-type epitaxial fin regions **110A** can have multiple sub-regions that can include SiGe and can differ from each other based on, for example, doping concentration, epitaxial growth process conditions, and/or relative concentration of Ge with respect to Si.

In some embodiments, n-type epitaxial fin regions **110B** can include Si and can be in-situ doped during an epitaxial growth process using n-type dopants, such as phosphorus and arsenic. In some embodiments, n-type epitaxial fin regions **110B** can have multiple n-type epitaxial fin sub-regions that can differ from each other based on, for example, doping concentration and/or epitaxial growth process conditions.

Referring to FIGS. 1A and 1B, stacked fin structures **104A** and **104B** can be current-carrying structures for respective GAA finFETs **102A** and **102B**. Channel regions of GAA finFETs **102A** and **102B** can be formed in portions of their respective stacked fin structures **104A** and **104B** underlying gate structures **112A** and **112B**. Epitaxial fin regions **110A** and **110B** can function as source/drain (S/D) regions of respective GAA finFETs **102A** and **102B**.

According to some embodiments, fin structures **104B** can be stacked on top of fin structures **104A** and isolated by isolation structure **120**, as shown in FIGS. 1A and 1B. In some embodiments, stacked fin structures **104A** and **104B** can provide independent control of dimensions and spacings of semiconductor layers **122A** and **122B** respectively. In some embodiments, the width and thickness of the semiconductor layers can be controlled to balance between power consumption and performance. For example, semiconductor layers **122A** can increase the width along a Y-axis (not shown) and thickness **122At** to improve performance of GAA finFETs **102A**. Semiconductor layers **122B** can decrease the width along another Y-axis (not shown) and thickness **122Bt** to reduce power and area consumption of GAA finFETs **102B**. In some embodiments, the thickness of and the spacing between the semiconductor layers can be controlled to balance conduction area and parasitic capacitance. In another example, semiconductor layers **122A** can increase thickness **122At** and spacing **122As** to increase a conduction area of GAA finFETs **102A**. Semiconductor layers **122B** can decrease thickness **122Bt** and spacing **122Bs** to reduce parasitic capacitance of GAA finFETs **102B**. In addition, semiconductor layers **122B** can have a different spacing from semiconductor layers **122A** for a different conductivity type work function metal fill.

Referring to FIGS. 1A and 1B, isolation structure **120** can be disposed between fin structures **104A** and **104B**. Accord-

ing to some embodiments, isolation structure **120** can isolate GAA finFETs **102A** and **102B**. According to some embodiments, isolation structure **120** can include insulating materials, such as silicon oxide, silicon nitride, a low-k material, other suitable insulating materials, and a combination thereof. In some embodiments, isolation structure **120** can include a first portion on stacked fin portions **108A** and a second portion on epitaxial fin regions **110A**. In some embodiments, isolation structure **120** can have a vertical dimension (e.g., thickness) **120t** along a Z-axis ranging from about 5 nm to about 10 nm.

Referring to FIGS. 1A and 1B, gate structures **112A** and **112B** can be multi-layered structures and can be wrapped around stacked fin portions **108A** and **108B**. In some embodiments, each of semiconductor layers **122A** and **122B** of stacked fin portions **108A** and **108B** can be wrapped around by one of gate structures **112A** and **112B** or one or more layers of one of gate structures **112A** and **112B** respectively, for which gate structures **112A** and **112B** can be referred to as “gate-all-around (GAA) structures” or “horizontal gate-all-around structures” and GAA finFETs **102A** and **102B** can be referred to as “GAA FETs” or “GAA finFETs.”

In some embodiments, gate structures **112A** and **112B** can include single layer or a stack of layers of gate electrode wrapping around semiconductor layers **122A** and **122B** respectively. In some embodiments, PFET **102A** can include p-type work function materials for gate electrode of gate structure **112A**. In some embodiments, NFET **102B** can include n-type work function materials for gate electrode of gate structure **112B**. In some embodiments, gate electrode of gate structures **112A** and **112B** can include, for example, aluminum (Al), copper (Cu), tungsten (W), titanium (Ti), tantalum (Ta), titanium nitride (TiN), tantalum nitride (Ta₂N₃), nickel silicide (NiSi), cobalt silicide (CoSi), silver (Ag), tantalum carbide (TaC), tantalum silicon nitride (TaSiN), tantalum carbon nitride (TaCN), titanium aluminum (TiAl), titanium aluminum nitride (TiAlN), tungsten nitride (WN), metal alloys, or combinations thereof.

Referring to FIGS. 1A and 1B, inner spacer structures **116A** and **116B** can be disposed between epitaxial fin regions **110A** and **110B** and portions of gate structures **112A** and **112B**, according to some embodiments. Inner spacer structures **116A** and **116B** can include a dielectric material, such as SiOC, SiCN, SiOCN, SiN, silicon oxide (SiO₂), silicon oxynitride (SiO_xN_y), and a combination thereof. In some embodiments, inner spacer structures **116A** and **116B** can include a single layer or multiple layers of insulating materials. In some embodiments, inner spacer structures **116A** and **116B** can isolate gate structures **112A** and **112B** and epitaxial fin regions **110A** and **110B**. In some embodiments, inner spacer structures **116A** and **116B** can have a thickness **116At** and **116Bt** along an X-axis ranging from about 3 nm to about 7 nm.

Referring to FIGS. 1A and 1B, gate interconnect **113** can be connected to a gate power supply line, and S/D interconnects **103** and **105** can be connected to S/D power supply lines. In some embodiments, gate interconnect **113** can be connected to a gate power supply line above GAA finFETs **102A** and **102B** and provide gate control to GAA finFETs **102A** and **102B**. In some embodiments, S/D interconnects **103** and **105** can be connected to S/D power supply lines buried in substrate **106**. Buried power supply lines can reduce standard cell routing and memory cell routing. For example, the drain side of GAA finFET **102A** can be

connected to a buried Vdd power supply line, and the source side of GAA finFET **102B** can be connected to a buried Vss power supply line.

In some embodiments, semiconductor device **100** can further include STI regions, gate dielectric layers, interlayer dielectric (ILD) layers, etch stop layer (ESL), S/D and gate contact structures, and other suitable layers and structures, which are not shown for simplicity.

FIG. **2A** illustrates an isometric view of a crossover-stacked semiconductor device **200A** with a vertical gate, according to some embodiments. As shown in FIG. **2A**, the fin structure of GAA finFET **202B** can extend along a direction different from the fin structure of GAA finFET **202A**, which can be referred to as crossover-stacked semiconductor device **200A**. In some embodiments, the direction of the fin structure of GAA finFET **202B** can rotate about 90 degrees from the direction of the fin structure of GAA finFET **202A**. For example, as shown in FIG. **2A**, the fin structure of GAA finFET **202B** can extend along an X-axis, and the fin structure of GAA finFET **202A** can extend along a Y-axis. According to some embodiments, compared with vertically stacked semiconductor device **100**, crossover-stacked semiconductor device **200A** can provide more simplicity in lithography and more compact metal interconnect to reduce parasitic resistance and capacitance, as well as more flexible place and route and improved placement legalization, in addition to independent control of fin structures dimensions and spacings.

FIG. **2B** illustrates an isometric view of a crossover-stacked semiconductor device **200B** with a rotated gate, according to some embodiments. As shown in FIG. **2B**, the fin structure and the gate structure of GAA finFET **202D** can extend along different directions from the fin structure and the gate structure of GAA finFET **202C**, respectively. In some embodiments, the direction of the fin structure of GAA finFET **202D** can rotate about 90 degrees from the direction of the fin structure of GAA finFET **202C**, and the direction of gate structure **212D** of GAA finFET **202D** can rotate about 90 degrees from the direction of gate structure **212C** of GAA finFET **202C**. For example, as shown in FIG. **2B**, the fin structure of GAA finFET **202C** can extend along an X-axis, and gate structure **212C** can extend along a Y-axis. The fin structure of GAA finFET **202D** can extend along a Y-axis, and gate structure **212D** can extend along an X-axis. In some embodiments, compared with crossover-stacked semiconductor device **200A**, crossover-stacked semiconductor device **200B** with a rotated gate can provide further compact metal interconnect to reduce parasitic resistance and capacitance by providing a shorter routing path, thus improving PPA performance. In some embodiments, compared with other planar GAA finFETs, crossover-stacked semiconductor device with a rotated gate can reduce the device area by about 30% to about 50%. In some embodiments, compared with other planar GAA finFETs, crossover-stacked semiconductor device **200B** can reduce the device area by about 30% to about 50%.

FIG. **3** is a flow diagram of a method **300** for fabricating a stacked semiconductor device, such as semiconductor devices **100**, **200A**, and **200B**, according to some embodiments. Additional fabrication operations may be performed between various operations of method **300** and may be omitted merely for clarity and ease of description. Some of the operations may be performed simultaneously, or in a different order than the ones shown in FIG. **3**. Additional processes can be provided before, during, and/or after method **300**, and that these additional processes can be briefly described herein. For illustrative purposes, the opera-

tions illustrated in FIG. **3** will be described with reference to the example fabrication process for fabricating vertically stacked semiconductor device **100** as illustrated in FIGS. **4-23**. FIGS. **4-23** are partial cross-sectional views of vertically stacked semiconductor device **100** along line B-B of vertically stacked semiconductor device **100** at various stages of its fabrication, according to some embodiments. Although FIGS. **4-27** illustrate fabrication process of vertically stacked semiconductor device **100**, method **300** can be applied to crossover-stacked semiconductor devices **200A** and **200B**, as well as other stacked semiconductor devices. Elements in FIGS. **4-23** with the same annotations as elements in FIGS. **1A** and **1B** are described above.

In referring to FIG. **3**, method **300** begins with operation **310** and the process of forming a first fin structure. For example, as shown in FIG. **4**, fin structure **104A*** can be formed on substrate **106**. Fin structure **104A*** can include semiconductor layers **412A** and **122A** stacked in an alternating configuration. Each of semiconductor layers **412A** and **122A** can be epitaxially grown on its underlying layer and can include semiconductor materials different from each other. In some embodiments, semiconductor layers **412A** and **122A** can include semiconductor materials similar to or different from substrate **106**. In some embodiments, semiconductor layers **412A** and **122A** can include semiconductor materials with oxidation rates and/or etch selectivity different from each other. In some embodiments, semiconductor layers **412A** can include silicon germanium (SiGe) with Ge in a range from about 20 atomic percent to about 40 atomic percent with any remaining atomic percent being Si. In some embodiments, semiconductor layers **122A** can include Si without any substantial amount of Ge.

Semiconductor layers **412A** and/or **122A** can be undoped or can be in-situ doped during their epitaxial growth process using (i) p-type dopants, such as boron, indium, or gallium; and/or (ii) n-type dopants, such as phosphorus or arsenic. For p-type in-situ doping, p-type doping precursors, such as diborane (B_2H_6), boron trifluoride (BF_3), and/or other p-type doping precursors can be used. For n-type in-situ doping, n-type doping precursors, such as phosphine (PH_3), arsine (AsH_3), and/or other n-type doping precursor, can be used. Semiconductor layers **412A** and **122A** can have respective thicknesses **412At** and **122At** along a Z-axis, each ranging from about 5 nm to about 12 nm and ranging from about 6 nm to about 10 nm respectively. Thicknesses **412At** and **122At** can be equal to or different from each other. Though three pairs of semiconductor layers **412A** and **122A** for fin structure **104A*** are shown in FIG. **4**, vertically stacked semiconductor device **100** can have any number of semiconductor layers **412A** and **122A**.

Referring to FIG. **3**, in operation **320**, a substrate layer is formed over the first fin structure. As shown in FIG. **4**, another semiconductor layer **420**, a doping layer **126**, and another pair of semiconductor layers **128** and **430** can be formed on top of fin structure **104A***. Doping layer **126** and semiconductor layer **128** can be referred to as substrate layer **127** for subsequent growth of an epitaxial layer and a second fin structure. Each of doping layer **126** and semiconductor layers **420**, **128**, and **430** can also be epitaxially grown on its underlying layer and can include semiconductor materials different from each other. In some embodiments, doping layer **126** and semiconductor layers **420**, **128**, and **430** can be undoped or can be in-situ doped similar to semiconductor layers **412A** and **122A**.

In some embodiments, semiconductor layer **420** can include silicon germanium (SiGe) with Ge in a range from about 10 atomic percent to about 20 atomic percent with any

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remaining atomic percent being Si. In some embodiments, semiconductor layers **126** can include Si without any substantial amount of Ge and doped with a conductivity type different from substrate **106**. For example, substrate **106** can be doped with n-type dopants, and doping layer **126** can be doped with p-type dopants.

In some embodiments, semiconductor layers **128** and **430** can be same as semiconductor layers **122A** and **412A**, respectively. In some embodiments, semiconductor layer **430** can serve as a capping layer to protect semiconductor layer **128**. In some embodiments, semiconductor layer **128** can be used to epitaxially grow additional semiconductor layers. In some embodiments, semiconductor layer **430** can include silicon germanium (SiGe) with Ge in a range from about 20 atomic percent to about 40 atomic percent with any remaining atomic percent being Si. In some embodiments, semiconductor layer **128** can include Si without any substantial amount of Ge. In some embodiments, semiconductor layer **128** can have a thickness **128t** along a Z-axis ranging from about 12 nm to about 20 nm. In some embodiments, semiconductor layer **430** can have a thickness **430t** along a Z-axis ranging from about 10 nm to about 16 nm.

Referring to FIG. 3, in operation **330**, an isolation structure can be formed between the first fin structure and the substrate layer. For example, FIGS. 5-14 show the formation of isolation structure **120** between fin structure **104A** and doping layer **126**. The formation of isolation structure **120** can include (i) vertical etch of semiconductor layers **122A**, **412A**, **128**, **420**, and **430** and doping layer **126**, (ii) lateral etch of semiconductor layers **412A** and **420**, (iii) formation of inner spacer structures **116A**, and (iv) filling of isolation structure **120**.

Referring to FIG. 5, semiconductor layers **122A**, **412A**, **128**, **420**, and **430** and doping layer **126** can be vertically etched to form an opening **532**. In some embodiments, S/D regions can be formed in opening **532** in subsequent processes. In some embodiments, opening **532** can have a horizontal dimension **532w** (e.g., width) along an X-axis direction ranging from about 12 nm to about 20 nm. In some embodiments, the vertical etch of the semiconductor layers **122A**, **412A**, **128**, **420**, and **430** and doping layer **126** can include a biased etching process. The biased etching process can be performed under a pressure in a range of about 1 mTorr to about 1000 mTorr, a power in range of about 50 W to about 1000 W, a bias voltage in a range of about 20 V to about 500 V, at a temperature in a range of about 40° C. to about 60° C., and using HBr and/or Cl₂ as etch gases. In some embodiments, the biased etching process can be directional and semiconductors layers **122A**, **412A**, **128**, **420**, and **430** and doping layer **126** can have substantially no lateral etch.

The vertical etch of semiconductors layers **122A**, **412A**, **128**, **420**, and **430** and doping layer **126** can be followed by a lateral etch of semiconductor layers **412A**, **420**, and **430**, as shown in FIG. 6. The lateral etch can be performed by a dry etching process, a wet etching process, or a combination thereof. The etching process can include multiple cycles of etching and purging processes, such as about 3 to about 20 cycles of etching and purging processes. The etching process in each cycle can include using a gas mixture having hydrogen fluoride (HF) and a fluorine-based gas. The gas ratio of HF to the fluorine-based gas in the gas mixture can range from about 4 to about 30. The purging process in each cycle can include using a gas mixture having HF and nitrogen (N₂). HF in the purging process can remove by-products and/or clean the surface of etched portions for

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subsequent cycles. The purging process can be longer than the etching process in each cycle.

In some embodiments, semiconductor layers **412A*** and **430*** can have a higher etch rate than semiconductor layer **420***. In some embodiments, higher Ge concentration in semiconductor layers **412A*** and **430*** can lead to a higher etch rate than semiconductor layer **420***. In some embodiments, the Ge concentration in semiconductor layers **412A*** and **430*** can be at least 10 atomic percent higher than the Ge concentration in semiconductor layer **420***. In some embodiments, semiconductor layers **412A*** can be laterally etched and form a lateral recess **412r** having a horizontal dimension **412d** (e.g., depth) along an X-axis ranging from about 8 nm to about 10 nm. In some embodiments, semiconductor layers **420*** can be laterally etched and form a lateral recess **420r** having a horizontal dimension **420d** (e.g., depth) along an X-axis ranging from about 2 nm to about 3 nm.

The lateral etch of semiconductor layers **412A**, **420**, and **430** can be followed by formation of inner spacer structures **116A**, as shown in FIGS. 7-8. The formation of inner spacer structures **116A** can further include (i) deposition of an inner spacer layer and (ii) lateral etch of the deposited inner spacer layer.

Referring to FIG. 7, inner spacer layer **116A*** can be deposited on the structure of FIG. 6. In some embodiments, the deposition process can include multiple cycles of deposition and etch processes. In each cycle, the etch process can follow the deposition process to prevent the formation of voids within inner spacer layer **116A*** by removing seams that can be formed within lateral recesses **420r** and **412r**. Inner spacer layer **116A*** can include a single layer or a stack of dielectric layers, deposited by atomic layer deposition (ALD), flowable chemical vapor deposition (FCVD), or other suitable methods. Inner spacer layer **116A*** can include dielectric material, such as SiOC, SiCN, SiOCN, SiN, silicon oxide (SiO₂), silicon oxynitride (SiO_xN), and a combination thereof. In some embodiments, after deposition, inner spacer layer **116A*** in lateral recess **412r** can have a horizontal dimension **412rt** (e.g., thickness) along an X-axis ranging from about 10 nm to about 15 nm. In some embodiments, after deposition, inner spacer layer **116A*** in lateral recess **420r** can have a horizontal dimension **420rt** (e.g., thickness) along an X-axis ranging from about 3 nm to about 5 nm.

The deposition of inner spacer layer **116A*** can be followed by a lateral etch to form inner spacer structures **116A** within lateral recess **412r**, as shown in FIG. 8. In some embodiments, the lateral etch of inner spacer layer **116A*** can include a dry etch process using a gas mixture of HF and nitrogen trifluoride (NF₃). After the lateral etch, inner spacer layer **116A*** can be removed from semiconductor layers **122A** and **128** and doping layer **126**. Lateral recess **420r** can have substantially no inner spacer layer and lateral recess **412r** can have inner spacer structures **116A** with a thickness **116At** ranging from about 5 nm to about 7 nm. Inner spacer structures **116A** in lateral recess **412r** can protect semiconductor layers **412A*** from being etched in subsequent processes of isolation layer **120** formation.

The formation of inner spacer structures **116A** can be followed by filling of isolation structure **120**, as shown in FIGS. 9-14. The filling of isolation structure **120** can further include (i) removing semiconductor layer **420*** to form an opening, (ii) fill the opening with an isolation layer, (iii) etching a portion of the isolation layer, (iv) formation of S/D epitaxial fin regions, and (v) forming another isolation layer on S/D epitaxial fin regions.

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Referring to FIG. 9, semiconductor layer 420* can be removed to form an opening 920. In some embodiments, removal of semiconductor layer 420* can be performed by a dry etching process, a wet etching process, or a combination thereof. The etching process can include multiple cycles of etching and purging processes, such as about 3 to about 20 cycles of etching and purging processes. The etching process in each cycle can include using a gas mixture having HF and a fluorine-based gas. The gas ratio of the gas mixture of HF to the fluorine-based gas can range from about 4 to about 30. The purging process in each cycle can include using a gas mixture having HF and nitrogen (N₂). HF in the purging process can remove by-products and/or clean the surface of etched portions for subsequent cycles. During removal of semiconductor layer 420*, semiconductor layers 412A* can be protected by inner spacer structures 116A. After removal of semiconductor layer 420*, opening 902 can be formed between semiconductor layer 122A and doping layer 126.

The removal of semiconductor layer 420* can be followed by fill opening 920 with an isolation layer 1020, as shown in FIG. 10. In some embodiments, isolation layer 1020 can be deposited on the structure of FIG. 9. In some embodiments, isolation layer 1020 can be deposited by ALD, CVD, or other suitable deposition methods to prevent formation of seams in isolation layer 1020 between semiconductor layer 122A and doping layer 126. In some embodiments, after the deposition, opening 920 can be filled with isolation layer 1020. In some embodiments, isolation layer 1020 can include insulation materials, such as silicon oxide, silicon nitride, a low-k material, other suitable insulating materials, and a combination thereof. Other deposition methods and insulating materials for isolation layer 1020 are within the scope and spirit of this disclosure.

The filling of opening 920 with isolation layer 1020 can be followed by etching a portion of isolation layer 1020, as shown in FIG. 11. In some embodiments, the etching process can include a dry etch process using a gas mixture of HF and ammonia (NH₃). The gas ratio of HF to NH₃ can range from about 1 to about 20. In some embodiments, isolation layer 1020 can be etched off from semiconductor layers 122A, 128, and 430*, doping layer 126, and inner spacer structures 116A. In some embodiments, isolation layer 1020* between semiconductor layer 122A and doping layer 126 can be formed after the etching process.

The etching of a portion of isolation layer 1020 can be followed by formation of epitaxial fin regions 110A, as shown in FIG. 12. In some embodiments, the formation of epitaxial fin regions 110A can include growth of epitaxial fin regions and etch of the epitaxial fin regions. In some embodiments, epitaxial fin regions can be grown on exposed surfaces of semiconductor layers 122A and 128 and doping layer 126. In some embodiments, the epitaxial fin regions grown on exposed surfaces can be etched to form epitaxial fin regions 110A. In some embodiments, the etch process can include dry etching and/or other directional etching methods. In some embodiments, the epitaxial fin regions can be etched below doping layer 126. In some embodiments, after the etch process, a vertical dimension 1020d (e.g., distance) along a Z-axis between the top surface of epitaxial fin regions 110A and the bottom of doping layer 126 can range from about 3 nm to about 5 nm. In some embodiments, vertical dimension 1020d can isolate epitaxial fin regions 110A of GAA finFET 102A from doping layer 126 and semiconductor layer 128 of GAA finFET 102B.

The formation of epitaxial fin regions 110A can be followed by forming another isolation layer on epitaxial fin

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regions 110A, as shown in FIGS. 13-14. Referring to FIG. 13, isolation layer 1320 can be deposited on the structure in FIG. 12. In some embodiments, isolation layer 1320 can be deposited by ALD, CVD, or other suitable methods. In some embodiments, isolation layer 1320 can include the same isolation materials as isolation layer 1020*. In some embodiments, isolation layer 1320 and semiconductor layer 430* can be polished and the polishing process can stop on semiconductor layer 128, as shown in FIG. 14. In some embodiments, the polishing process can include a chemical-mechanical polishing (CMP) process. In some embodiments, semiconductor layer 430* can be damaged during previous processes and thus polished away for subsequent semiconductor layer epitaxial growth on semiconductor layer 128. In some embodiments, semiconductor layer 430* can also be removed in subsequent processes of nanosheet/nanowire shaped semiconductor layer formation. In some embodiments, isolation structure 120 can be formed after the polishing process. In some embodiments, isolation structure 120 can include a first portion between semiconductor layer 122A and stacked fin portions 108A. In some embodiments, isolation structure 120 can include a second portion on epitaxial fin regions 110A.

The formation of isolation structure 120 can be followed by metal gate formation, as shown in FIGS. 15 and 16. In some embodiments, metal gate formation can include nanosheet/nanowire shaped semiconductor layers 122A formation and metal gate fill. Referring to FIG. 15, semiconductor layers 412A* can be removed and form openings 1512 between semiconductor layers 122A. In some embodiments, semiconductor layers 412A* can be removed by an etching process using a gas mixture having HF and a fluorine-based gas. In some embodiments, the gas ratio of the HF to the fluorine-based gas in the gas mixture can range from about 60 to about 100.

The formation of nanosheet/nanowire shaped semiconductor layers 122A can be followed by a metal gate fill, as shown in FIG. 16. Prior to the metal gate fill, a gate dielectric layer can be formed on semiconductor layers 122A. In some embodiments, the gate dielectric layer can wrap around nanosheet/nanowire shaped semiconductor layers 122A and can include an interfacial layer (IL) and a high-k dielectric layer. Referring to FIG. 16, the metal gate can be filled in openings 1512 to form gate structures 112A. In some embodiments, gate structures 112A can also wrap around nanosheet/nanowire shaped semiconductor layers 122A and can include n-type or p-type work function metal.

Referring to FIG. 3, in operation 340, an epitaxial layer is formed in contact with the substrate layer and the isolation structure. For example, as shown in FIG. 17, epitaxial layer 130 can be formed in contact with substrate layer 127 and isolation structure 120. Substrate layer 127 can include semiconductor layer 128 and doping layer 126. In some embodiments, epitaxial layer 130 can be epitaxially grown similar to semiconductor layers 122A. In some embodiments, epitaxial layer 130 can include Si without any substantial amount of Ge. In some embodiments, epitaxial layer 130 can be epitaxially grown on semiconductor layer 128 and merge over the portion of isolation structure 120 on epitaxial fin regions 110A. In some embodiments, epitaxial layer 130 can have a thickness 130t along a Z-axis ranging from about 10 nm to about 20 nm.

Referring to FIG. 3, in operation 350, a second fin structure is formed over the first fin structure and in contact with the epitaxial layer. For example, as shown in FIG. 17, fin structure 104B* can be formed in contact with epitaxial layer 130. In some embodiments, isolation structure 120 can

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isolate fin structure **104B*** and fin structure **104A**. In some embodiments, fin structure **104B*** can have thickness **122Bt** and spacing **122Bs** along a Z-axis for semiconductor layers **122B*** different from thickness **122At** and spacing **122Bs** for semiconductor layers **122A** of fin structure **104A**, respectively.

Stacked fin structures **104A** and **104B*** can provide independent control of semiconductor layer dimension and spacing for each fin structure. In some embodiments, the width and thickness of the semiconductor layers can be controlled to provide a balance between power consumption and performance. For example, semiconductor layers **122A** can increase the width along a Y-axis (not shown) and thickness **122At** to improve performance of GAA finfets **102A**. Semiconductor layers **122B*** can decrease the width along another Y-axis (not shown) and thickness **122Bt** to reduce power and area consumption of GAA finfets **102B**. In some embodiments, the thickness of and the spacing between the semiconductor layers can be controlled to balance conduction area and parasitic capacitance. In another example, semiconductor layers **122A** can increase thickness **122At** and spacing **122As** to increase conduction area of GAA finfets **102A**. Semiconductor layers **122B*** can decrease thickness **122Bt** and spacing **122Bs** to reduce parasitic capacitance of GAA finfets **102B**. In addition, semiconductor layers **122B*** can have a different spacing from semiconductor layers **122A** for a different conductivity type work function metal fill.

In some embodiments, fin structure **104B*** can be vertically stacked on fin structure **104A** and can extend along a same direction as fin structure **104A**, as shown in FIG. 17. In some embodiments, fin structure **104B*** can be crossover-stacked on fin structure **104A** and can extend along a direction different from the direction of fin structure **104A**. For example, fin structure **104B*** can extend along a Y-axis and fin structure **104A** can extend along an X-axis. According to some embodiments, compared with vertically stacked fin structures **104B*** and **104A**, crossover-stacked fin structures **104B*** and **104A** can provide more simplicity and compact in lithography and metal interconnect processes, which allow more flexible place and route for improved placement legalization and interconnect routing, in addition to independent control of semiconductor layer dimensions and spacings.

The formation of the second fin structure can be followed by a semiconductor layer lateral etch, inner spacer structure deposition and etch, epitaxial fin regions deposition and etch, formation of nanosheet/nanowire shaped semiconductor layer, and metal gate formation. FIG. 1B illustrates a cross-section view after metal gate formation of the second fin structure. In some embodiments, the semiconductor layer lateral etch, inner spacer structure deposition and etch, epitaxial fin regions deposition and etch, formation of nanosheet/nanowire shaped semiconductor layer, and metal gate formation of GAA finFET **102B** can be similar to the processes to form GAA finFET **102A**. With stacked GAA finFETs **102A** and **102B**, GAA finFETs **102B** can have independent control of inner spacer structure **112B** and gate structure **122B**. In some embodiments, gate structure GAA finFET **102B** can extend along a direction different from gate structure of GAA finFET **102A**. For example, as shown in FIG. 2B, gate structure **212D** can extend along an X-axis, and gate structure **212C** can extend along a Y-axis. According to some embodiments, crossover-stacked semiconductor device with a rotated gate can provide further compact metal interconnect to reduce parasitic resistance and capacitance with shorter routing path, thus improving PPA performance.

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In some embodiments, compared with other planar GAA finFETs, crossover-stacked semiconductor device with a rotated gate can reduce the device area by about 30% to about 50%.

Referring to FIGS. 18-23, additional isolation structures can be formed between GAA finFETs **104A** and **104B**. As shown in FIG. 18, an epitaxial layer **1830** can be grown on the structure in FIG. 16 after metal gate formation. In some embodiments, epitaxial layer **1830** can include semiconductor material similar to semiconductor layer **128** and have a thickness **1830t** along a Z-axis ranging from about 10 nm to about 30 nm. In some embodiments, epitaxial layer **1830** can cover semiconductor layer **128** and isolation structure **120** for subsequent semiconductor layer growth. A sacrificial fin structure **1837** including semiconductor layers **1838** and **1840** stacked in an alternating configuration can be formed on epitaxial layer **2246**. In some embodiments, sacrificial fin structure **1837** can be formed similar to fin structure **104B*** illustrated in FIG. 17. In some embodiments, semiconductor layers **1838** can include silicon germanium (SiGe) with Ge in a range from about 20 atomic percent to about 40 atomic percent with any remaining atomic percent being Si. In some embodiments, semiconductor layers **1840** can include Si without any substantial amount of Ge. In some embodiments, semiconductor layers **1838** and **1840** can be vertically etched, as shown in FIG. 5. In some embodiments, semiconductor layer **1838** can have a thickness **1838t** along a Z-axis ranging from about 20 nm to about 25 nm. In some embodiments, semiconductor layer **1840** can have a thickness **1840t** along a Z-axis ranging from about 3 nm to about 7 nm.

The formation of sacrificial fin structure **1837** can be followed by removal of semiconductor layers **1838**, as shown in FIG. 19. The removal of semiconductor layers **1838** can be performed by an etching process similar as the formation of nanosheet/nanowire shaped semiconductor layer illustrated in FIG. 15.

The removal of semiconductor layers **1838** can be followed by formation of isolation structure **2020**, as shown in FIGS. 20 and 21. The formation of isolation structure **2020** can include deposition of isolation layer **2020*** and CMP of isolation layer **2020***. Referring to FIG. 20, isolation layer **2020*** can be deposited similar to isolation layer **1320** illustrated in FIG. 13. Referring to FIG. 21, isolation structure **2020** can be formed by a similar CMP process as isolation layer **120**. According to some embodiments, isolation structures **120** and **2020** can improve isolation between top and bottom GAA finFETs.

The formation of isolation structure **2020** can be followed by another epitaxial layer growth and formation of fin structure **104B***, as shown in FIGS. 22 and 23. Referring to FIG. 22, epitaxial layer **2242** can be grown on the structure in FIG. 21. In some embodiments, epitaxial layer **2242** can include semiconductor material similar to semiconductor layer **1840** and have a thickness **2242t** along a Z-axis ranging from about 10 nm to about 30 nm. In some embodiments, epitaxial layer **2242** can cover semiconductor layer **1840** and isolation structure **2020** for subsequent semiconductor layer growth. In some embodiments, epitaxial layer **2242** can improve isolation between top and bottom GAA finFETs. Referring to FIG. 23, fin structure **104B*** can be grown on epitaxial layer **2242**. Subsequent processes can be performed on fin structure **104B*** to form GAA finFET **102A**.

Various embodiments in accordance with the present disclosure provide methods for forming a stacked semiconductor device, such as vertically stacked semiconductor

device **100** and crossover-stacked semiconductor devices **200A** and **200B**. According to some embodiments, vertically stacked semiconductor device **100** can include a top fin structure **104B** along an X-axis vertically stacked on top of a bottom fin structure **104A** along another X-axis. In some embodiments, the vertically stacked fin structures **104A** and **104B** can each independently control their nanosheet/nanowire dimensions and spacings. In some embodiments, the top fin structure along a direction can be stacked on top of a bottom fin structure along another direction rotated by some degrees, such as about 90 degrees. In some embodiments, a crossover-stacked semiconductor device, such as **200A** and **200B**, can provide compact metal interconnect place and route for the top and bottom fin structures, therefore improving PPA performance. In some embodiments, crossover-stacked semiconductor device **200B** can include a top gate structure rotated by some degrees relative to the bottom gate structure, such as about 90 degrees. In some embodiments, crossover-stacked semiconductor device **200B** with a rotated gate can provide further compact metal interconnect route and place to reduce parasitic resistance and capacitance, thus improving PPA performance. In some embodiments, isolation layer **120** can isolate fin structure **104B** and fin structure **104A**. In some embodiments, additional isolation structure **2020** can improve the isolation between fin structure **104B** and fin structure **104B**. In some embodiments, compared with other planar GAA finFETs, crossover-stacked semiconductor device **200B** can reduce the device area by about 30% to about 50%.

In some embodiments, a semiconductor device includes a first fin structure, an isolation structure in contact with a top surface of the first fin structure, a substrate layer in contact with the isolation structure, an epitaxial layer in contact with the isolation structure and the substrate layer, and a second fin structure above the first fin structure and in contact with the epitaxial layer.

In some embodiments, a semiconductor device includes a first fin structure, a first isolation structure on a top surface of the first fin structure, a substrate layer on the first isolation structure, a first epitaxial layer on the first isolation structure and the substrate layer, a second isolation structure on the first epitaxial layer, a second epitaxial layer on the second isolation structure, and a second fin structure above the first fin structure and in contact with the second epitaxial layer.

In some embodiments, a method includes forming a first fin structure, forming a substrate layer over the first fin structure, forming an isolation structure between the substrate layer and the first fin structure, forming an epitaxial layer in contact with the isolation structure and the substrate layer, and forming a second fin structure above the first fin structure and in contact with the epitaxial layer.

It is to be appreciated that the Detailed Description section, and not the Abstract of the Disclosure section, is intended to be used to interpret the claims. The Abstract of the Disclosure section may set forth one or more but not all possible embodiments of the present disclosure as contemplated by the inventor(s), and thus, are not intended to limit the subjoined claims in any way.

The foregoing disclosure outlines features of several embodiments so that those skilled in the art may better understand the aspects of the present disclosure. Those skilled in the art will appreciate that they may readily use the present disclosure as a basis for designing or modifying other processes and structures for carrying out the same purposes and/or achieving the same advantages of the embodiments introduced herein. Those skilled in the art will also realize that such equivalent constructions do not depart

from the spirit and scope of the present disclosure, and that they may make various changes, substitutions, and alterations herein without departing from the spirit and scope of the present disclosure.

What is claimed is:

1. A semiconductor device, comprising:
 - a first stack of semiconductor layers;
 - an isolation structure on a top surface of the first stack of semiconductor layers;
 - a substrate layer on a top surface of the isolation structure;
 - an epitaxial layer on the substrate layer, wherein the isolation structure extends through the substrate layer and is in contact with the epitaxial layer; and
 - a second stack of semiconductor layers above the epitaxial layer and the first stack of semiconductor layers.
2. The semiconductor device of claim 1, further comprising a gate structure wrapped around the first and second stacks of semiconductor layers.
3. The semiconductor device of claim 1, further comprising:
 - a first gate structure wrapped around the first stack of semiconductor layers and having a first gate length; and
 - a second gate structure wrapped around the second stack of semiconductor layers and having a second gate length different from the first gate length.
4. The semiconductor device of claim 1, wherein the first stack of semiconductor layers extends along a first direction, and wherein the second stack of semiconductor layers extends along a second direction parallel to the first direction.
5. The semiconductor device of claim 1, wherein the first stack of semiconductor layers extends along a first direction, and wherein the second stack of semiconductor layers extends along a second direction different from the first direction.
6. The semiconductor device of claim 1, wherein each layer of the first stack of semiconductor layers has a first thickness, and wherein each layer of the second stack of semiconductor layers has a second thickness different from the first thickness.
7. The semiconductor device of claim 1, wherein each layer of the first stack of semiconductor layers has a first width, and wherein each layer of the second stack of semiconductor layers has a second width different from the first width.
8. The semiconductor device of claim 1, wherein the first stack of semiconductor layers has a first spacing between each semiconductor layer, and wherein the second stack of semiconductor layers has a second spacing between each semiconductor layer, the second spacing being different from the first spacing.
9. The semiconductor device of claim 1, wherein the isolation structure comprises silicon oxide.
10. A semiconductor device, comprising:
 - a first stack of semiconductor layers;
 - a first isolation structure on a top surface of the first stack of semiconductor layers;
 - a substrate layer on the first isolation structure;
 - a first epitaxial layer on the substrate layer, wherein the first isolation structure extends through the substrate layer and is in contact with the first epitaxial layer;
 - a second isolation structure on the first epitaxial layer;
 - a second epitaxial layer on the second isolation structure, wherein the first epitaxial layer is in contact with the first isolation structure and the second isolation structure; and

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a second stack of semiconductor layers on the second epitaxial layer.

11. The semiconductor device of claim 10, further comprising:

a first gate structure wrapped around the first stack of semiconductor layers having a first gate length; and
a second gate structure wrapped around the second stack of semiconductor layers having a second gate length different from the first gate length.

12. The semiconductor device of claim 10, wherein the first stack of semiconductor layers extends along a first direction, and wherein the second stack of semiconductor layers extends along a second direction parallel to the first direction.

13. The semiconductor device of claim 10, wherein the first stack of semiconductor layers are along a first direction, and wherein the second stack of semiconductor layers are along a second direction different from the first direction.

14. The semiconductor device of claim 10, wherein each layer of the first stack of semiconductor layers has a first thickness, and wherein each layer of the second stack of semiconductor layers has a second thickness different from the first thickness.

15. The semiconductor device of claim 10, wherein each layer of the first stack of semiconductor layers has a first width, and wherein each layer of the second stack of semiconductor layers has a second width different from the first width.

16. The semiconductor device of claim 10, wherein the substrate layer comprises a doping layer and a semiconductor layer.

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17. A semiconductor device, comprising:

a first stack of semiconductor layers;
first epitaxial regions in contact with end portions of the first stack of semiconductor layers;

an isolation structure in contact with the first stack of semiconductor layers and the first epitaxial regions;

a substrate layer on the isolation structure, wherein the isolation structure extends through the substrate layer;

an epitaxial layer in contact with the isolation structure and the substrate layer;

a second stack of semiconductor layers above the first stack of semiconductor layers; and

second epitaxial regions on the epitaxial layer, wherein the second epitaxial regions are in contact with end portions of the second stack of semiconductor layers.

18. The semiconductor device of claim 17, wherein each layer of the first stack of semiconductor layers has a first thickness, and wherein each layer of the second stack of semiconductor layers has a second thickness different from the first thickness.

19. The semiconductor device of claim 17, wherein each layer of the first stack of semiconductor layers has a first width, and wherein each layer of the second stack of semiconductor layers has a second width different from the first width.

20. The semiconductor device of claim 17, further comprising a gate structure wrapped around the first and second stacks of semiconductor layers.

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